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TECHNICAL REPORT NO. 70-6

DESIGN OF PORTABLE STRAINMETER SYSTEM

Special Report, Project VT/8703

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TELEDYNE GEOTECH

TECHNICAL REPORT NO. 70-6

SPECIAL REPORT, VT/8703

DESIGN OF PORTABLE STRAINMETER SYSTEM

by

Robert C. Shopland

Sponsored by

Advanced Research Projects Agency
Nuclear Test Detection Office
ARPA Order No. 624

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TELEDYNE GEOTECH
3401 Shiloh Road
Garland, Texas

13 March 1970

<u>IDENTIFICATION</u>

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ARPA Code No:	8F10
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Program Manager:	R. G. Reakes, BR1-2561, Garland, Texas

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ILLUSTRATIONS, Continued

ILLUSTRATIONS, Continued

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ABSTRACT

Six portable strainmeter systems were designed and built for deployment in mine tunnels and shallow trenches to measure strains induced by high yield underground events at epicentral distances as short as 30 km. The system is designed to detect earth strains of 5×10^{-10} or smaller over a horizontal interval of 6 meters in the period range 10 seconds to dc, and to record the signals on magnetic tape. Strains are detected by a variable-capacitance transducer attached to a quartz-tube translating member. Output signals are maintained within a dynamic range of 30 dB for an input-signal range of 66 dB by an offset-biasing technique which uses a precision voltage-level detector and a digital-to-analog converter. Temperature measurements are resolvable to within 0.001-degree centigrade by the same offset-biasing technique. The strainmeter is calibrated with a temperature-compensated electromagnetic-calibrator mounted at the fixed end of the quartz tubing. The strain detector is calibrated and the capacitor plates positioned over a range of 12×10^{-6} meters in steps of 5×10^{-9} meters by use of a stepping motor and motion reducer.

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SPECIAL REPORT, VT/8703
DESIGN OF PORTABLE STRAINMETER SYSTEM

1. INTRODUCTION

This is a special report describing the work undertaken in the period 15 August to 15 December 1969 to design, fabricate and laboratory test six portable strainmeter systems. The report is submitted in compliance with Sequence Number B004 of Contract Data Requirements List, Contract F33657-69-C-0757, Amendment 002. The Statement of Work is included as Appendix 1.

2. GENERAL DESCRIPTION OF SYSTEM

The portable strainmeter system is designed to detect earth strains of 5×10^{-10} or smaller over a horizontal interval of 6 meters in the period range 10 seconds to dc, and to record the signals on magnetic tape. The design allows strains over a 66 dB range to be recorded on a high-gain channel in a range 5×10^{-10} to 1×10^{-6}, and over a 34 dB range on a low-gain channel from approximately 1×10^{-7} to 5×10^{-6}. Quasi-static step strains as large as 1×10^{-6} and residual strains as small as 5×10^{-10} are detected by a variable-capacitance transducer and recorded on the high-gain channel. Step strains exceeding 1×10^{-6} are recorded on the low-gain channel.

The signal levels for step strains at epicentral distances of 30 and 120 km for earthquakes and explosions of Richter magnitude 6.5, based on data from Wideman and Major (1967) and Romig et al (1969), were used to establish specifications on filtering, transducer sensitivity, gain-control range, and recentering. Data by Fluker (1958) were used to predict diurnal and seasonal temperature effects. Strain observations at the 4-meter deep trench installation at the Wichita Mountains Observatory were used to estimate the coefficient of expansion of granophyre. Benioff (1959) points out the possibility of occurrence of relatively large strains induced at depth by temperature variation of surface layers. Consequently, provision is made in the portable strain system to measure four points in the temperature regime.

Basically, the portable strainmeter system (figure 1) consists of a strainmeter housed in a trench or tunnel; a recording facility; a thermoelectric generator and propane fuel supply; and mobile service instrumentation. Unattended operation for 2 weeks is provided. Four weeks of unattended operation is possible by doubling the 100-lb supply of propane fuel. Signals can be monitored and the strainmeter controlled and calibrated from a service vehicle. A block diagram of the system components is shown as figure 2. System characteristics are described in Appendix 2.

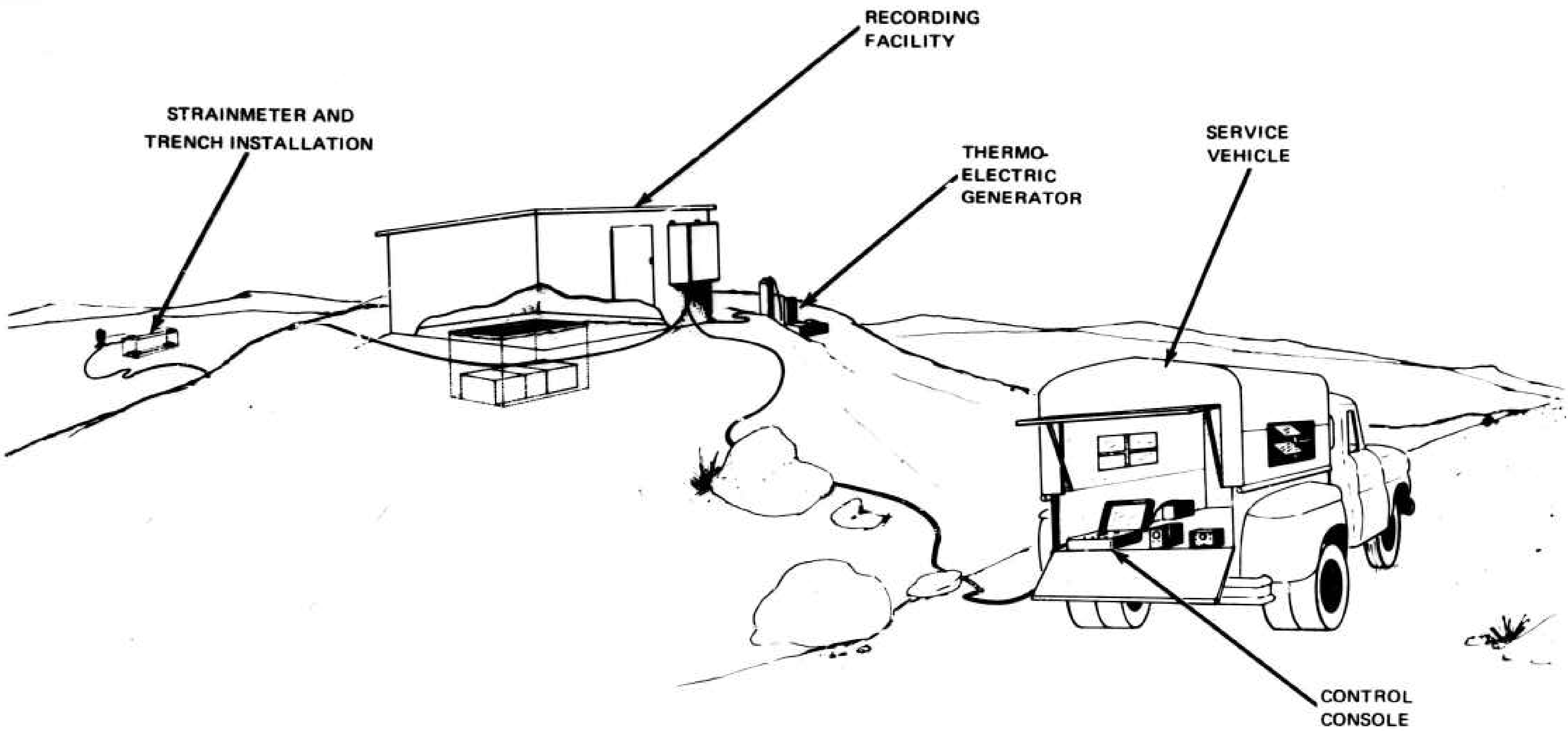

Figure 1. Pictorial of portable strainmeter system

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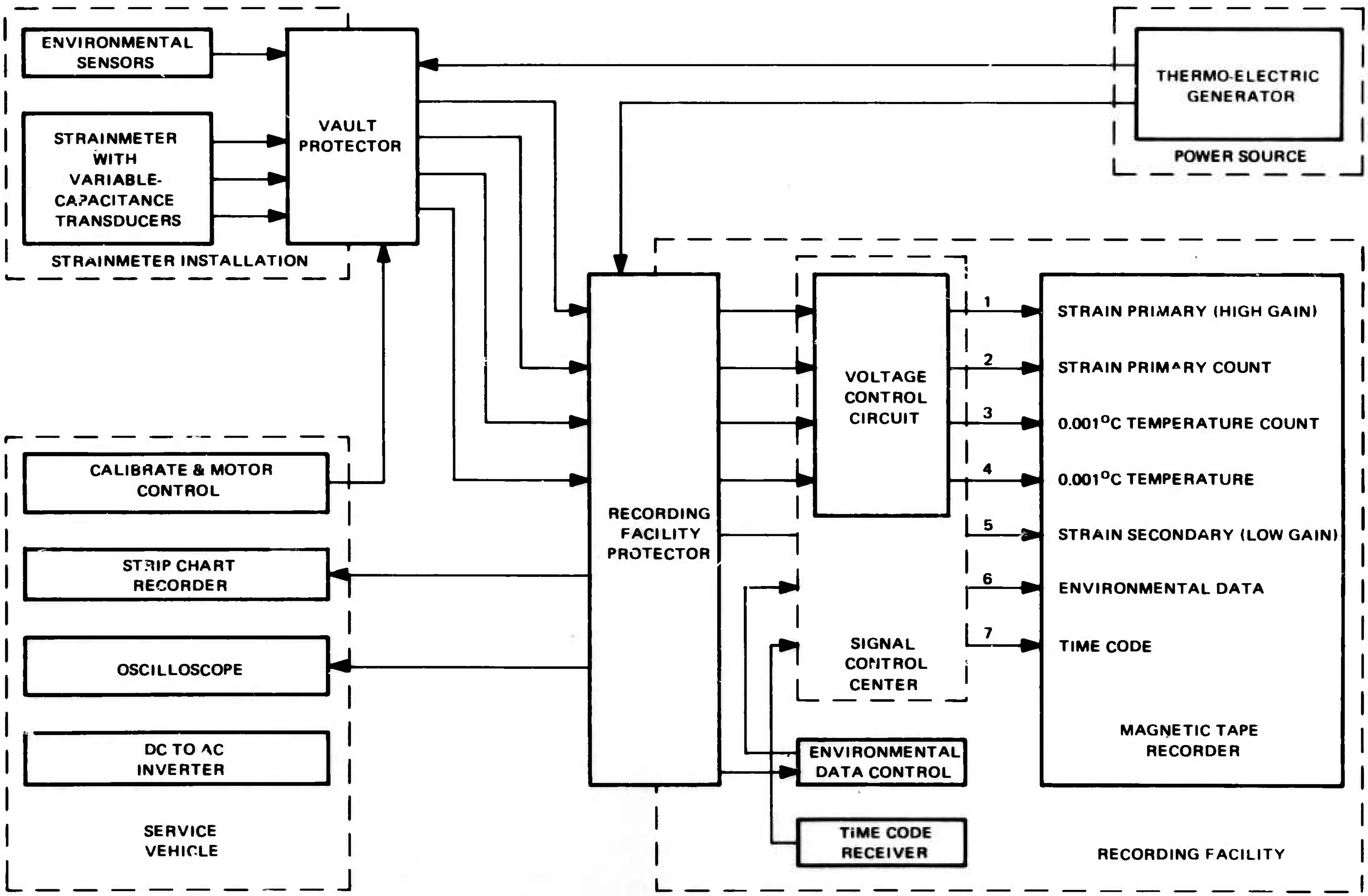

Figure 2. Block diagram of portable strainmeter system

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Strains are detected by a dual variable-capacitance transducer (VCT) attached to a quartz-tube translating member. Differential displacements of the earth, sensed by capacitor plates, are converted to variations in oscillator pulse widths. The pulse widths are averaged and amplified before being transmitted by cable from a tunnel or a buried-trench installation to a nearby recording facility. A voltage control circuit maintains the output signal within a dynamic range of 30 dB for an input-signal range of 66 dB. This is accomplished by an offset-biasing technique using a precision level detector and a digital-to-analog converter. The number and polarity of the offset increments are recorded on a separate track of the tape recorder for restoration of the input signal.

The most critical design problems were encountered in providing the following:

a. A transducer with sufficient sensitivity, low noise level, and linear range;

b. Maintaining the output signal within the useful operating range of the recorder;

c. Sufficient precision in recentering the transducer;

d. Maximum isolation of instruments from temperature change, and adequate range and resolution of the temperature monitors.

Ideally, the strainmeters should be operated in deep mines. However, even near-surface mines with short tunnels are not readily available, and normally are not in the correct locations for optimum deployment patterns. In compromising between economic and technical requirements the strainmeter is designed to operate in a buried trench at a depth of 2 to 3 meters or in a mine with equal or better temperature stability. If one assumes that the temperature coefficients of the quartz tubing and the rock differ by at least a factor of two, as suggested by strain measurements in a 4-meter deep trench at the Wichita Mountains Observatory in Lawton, Oklahoma, then a resultant coefficient of at least 3 microns per degree Centigrade exists in a 6-meter interval. To correct the strain data for temperature changes and still maintain strain resolution to within 5×10^{-10}, tube temperature must be monitored with a resolution of 0.001 degree Centigrade. To monitor a sufficient range of temperature with such a high degree of resolution, the temperature signal is fed into an offset biasing circuit which maintains the signal within the linear range of the tape recorder. The number and polarity of the offset increments are recorded on a separate track of the tape recorder to permit temperature compensation of the strain data during later processing. Three additional environmental sensors monitor temperature with a resolution of 0.01°C at the strain transducer; with a resolution of 0.1°C in the strainmeter vault; and with a resolution of 1°C for recording outside air temperature. Wind speeds or pressure changes are recorded on a fourth environmental channel. Environmental data from the four sensors are time-shared and recorded on channel No. 6 of the tape recorder. Time signals from WWVB are recorded on a separate track. Channel designations are listed in table 1. The radio channel (No. 7) and the two channels recording offset counts (No. 2 and No. 3) use "DIRECT RECORD" electronics which have a higher frequency response (50 Hz) than FM electronics (5 Hz).

Table 1. Magnetic-tape recorder - channel designations

Channel	Information	Mode
1	Strain (high gain)	FM
2	Strain offset count	Direct
3	0.001°C offset count	Direct
4	0.001°C	FM
5	Strain (low gain)	FM
6	Environmental	FM
7	Time code (WWVB)	Direct

3. STRAINMETER VAULT

3.1 TRENCH INSTALLATION

The strainmeter vault is composed of either a sealed-off section of a mine tunnel or a covered trench. In the latter case, the trench is excavated in competent bedrock to a depth of 2.6 meters and a width of 2 to 2.6 meters. The strainmeter is housed in a subtrench approximately 3 feet wide, as shown in figure 3.

The strainmeter vault is designed to house one transducer assembly; one calibrator; a quartz rod, 6 meters long; and insulation necessary to maintain diurnal temperature drifts within an ideal 0.003°C. The transducer and calibrator vaults are 1.3 meters square and 2.6 meters deep. They are constructed using 4 x 4 inch lumber at the corners and 3/4 inch exterior plywood for the walls with 2 x 4 inch braces on 0.6 m centers. The top 2.3 meters of space in each vault is utilized as an accessway to the seismometer. During operation, this area is filled by two blocks of polystyrene insulation. Figure 4 is a photograph of the completed trench installation prior to backfilling.

A tunnel made of culvert, plywood and steel beams is designed to house the 6 meter long quartz tube. Tunnel rigidity is achieved using a half-section of 12-gauge corrugated steel culvert which is placed on 3/4-inch thick plywood. This half-cylinder is supported by six frames which are made of 2 x 2-inch steel "Tee" beam stock. Each frame consists of a 1.3 meter crossbeam bolted to two vertical beams which are mounted in holes drilled in the bedrock. After placement, the tunnel cover is approximately 0.8 meters above the floor of the subtrench. This assembly provides an economical, earth-retaining structure which is easily installed. A cross-section of the tunnel is shown in figure 5. Thermal insulation for the tunnel is achieved by filling the top section with blocks of expanded polystyrene. Sheets of this material are also used to enclose the quartz tube. Figure 6 shows the steel support beams and the insulation which encloses the tube.

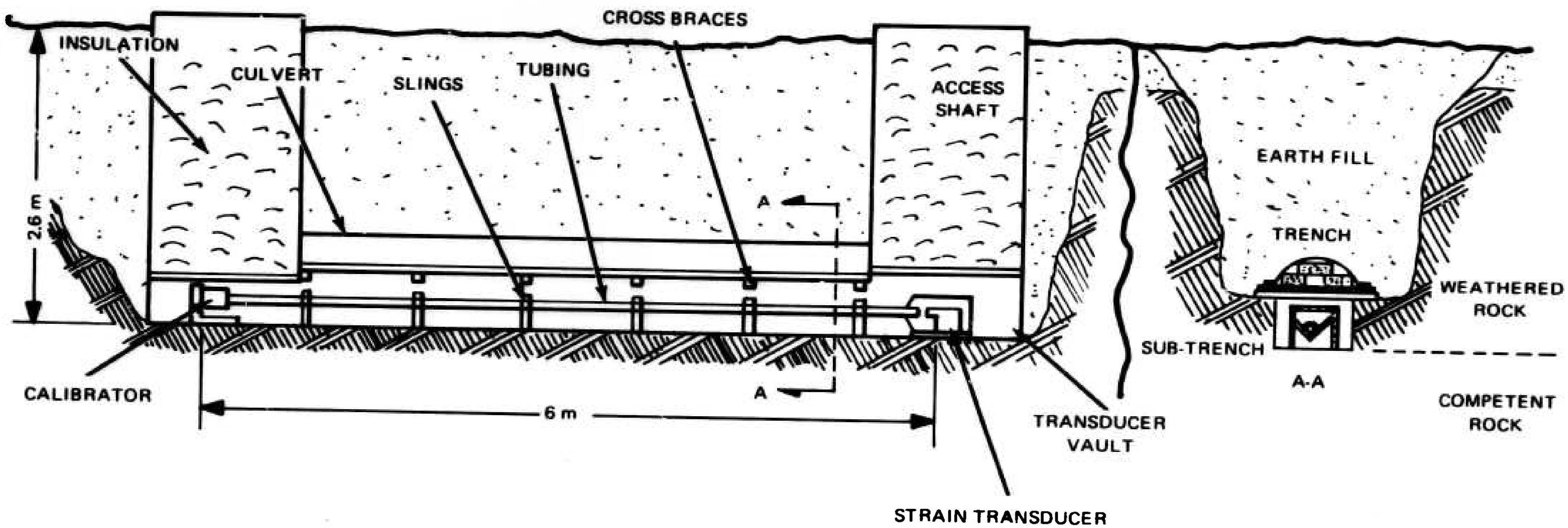

Figure 3. Strainmeter in trench installation

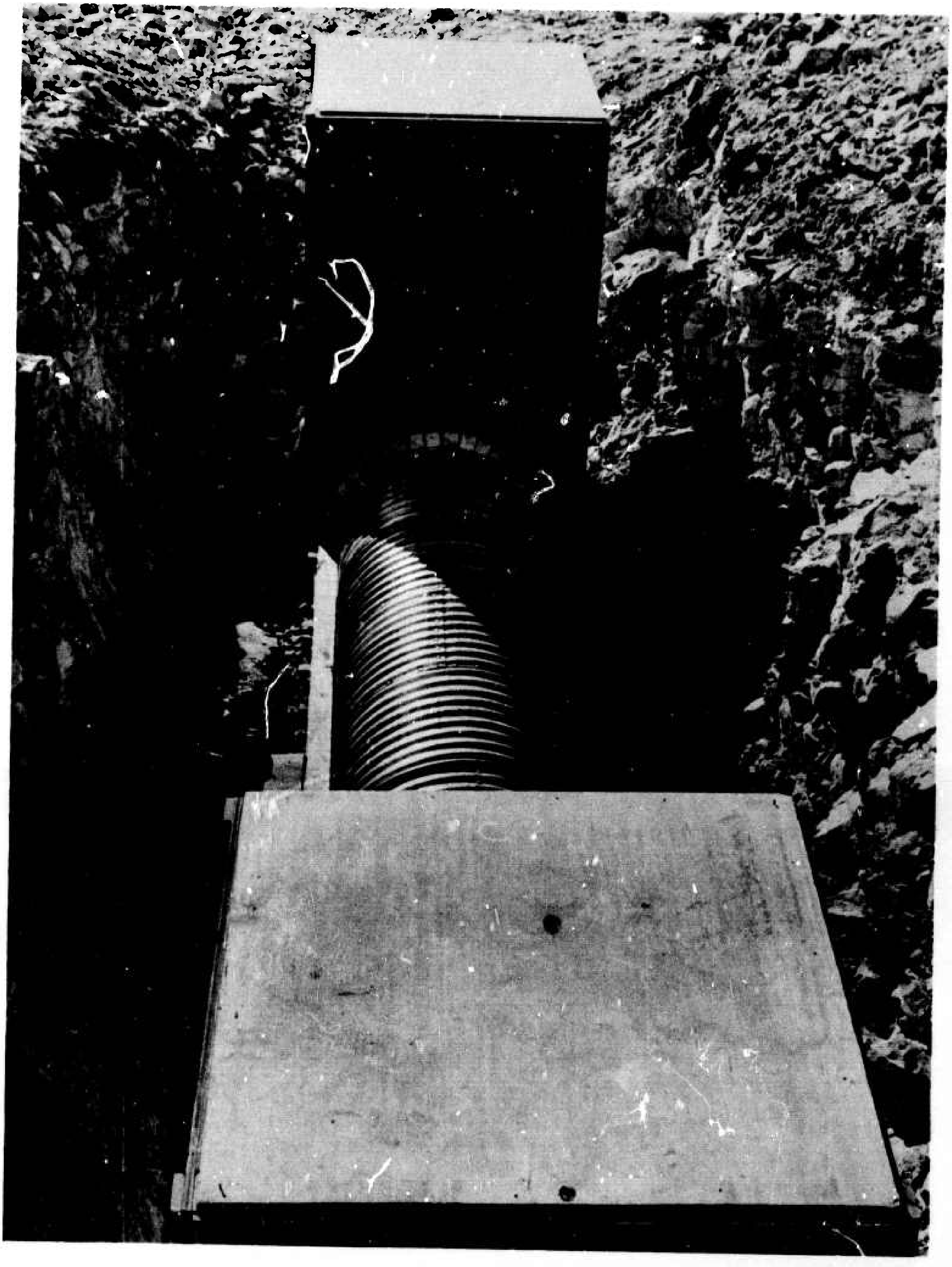

Figure 4. Complete trench installation before backfilling

G 5685

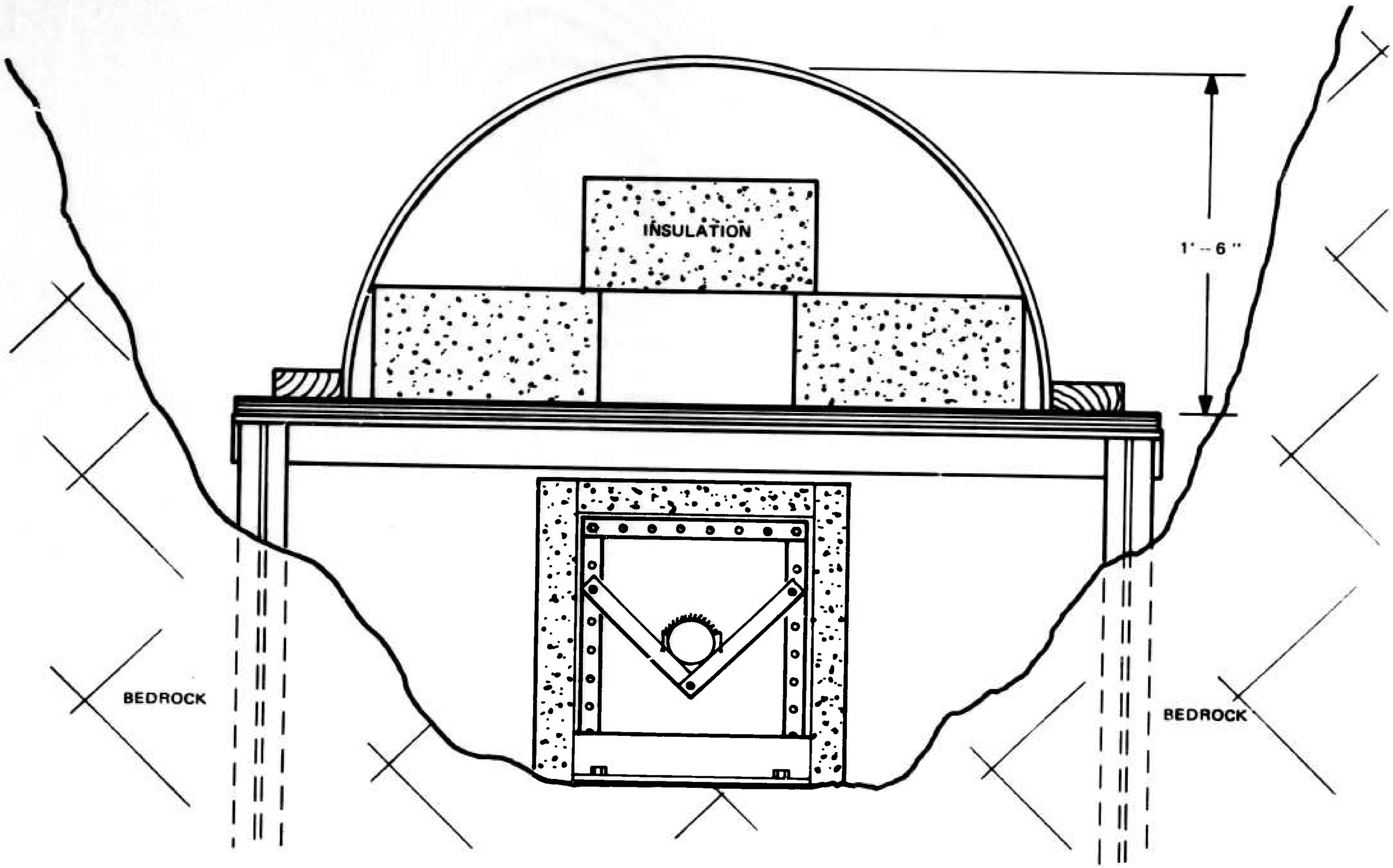

Figure 5. Cross section of strainmeter tunnel in a trench installation

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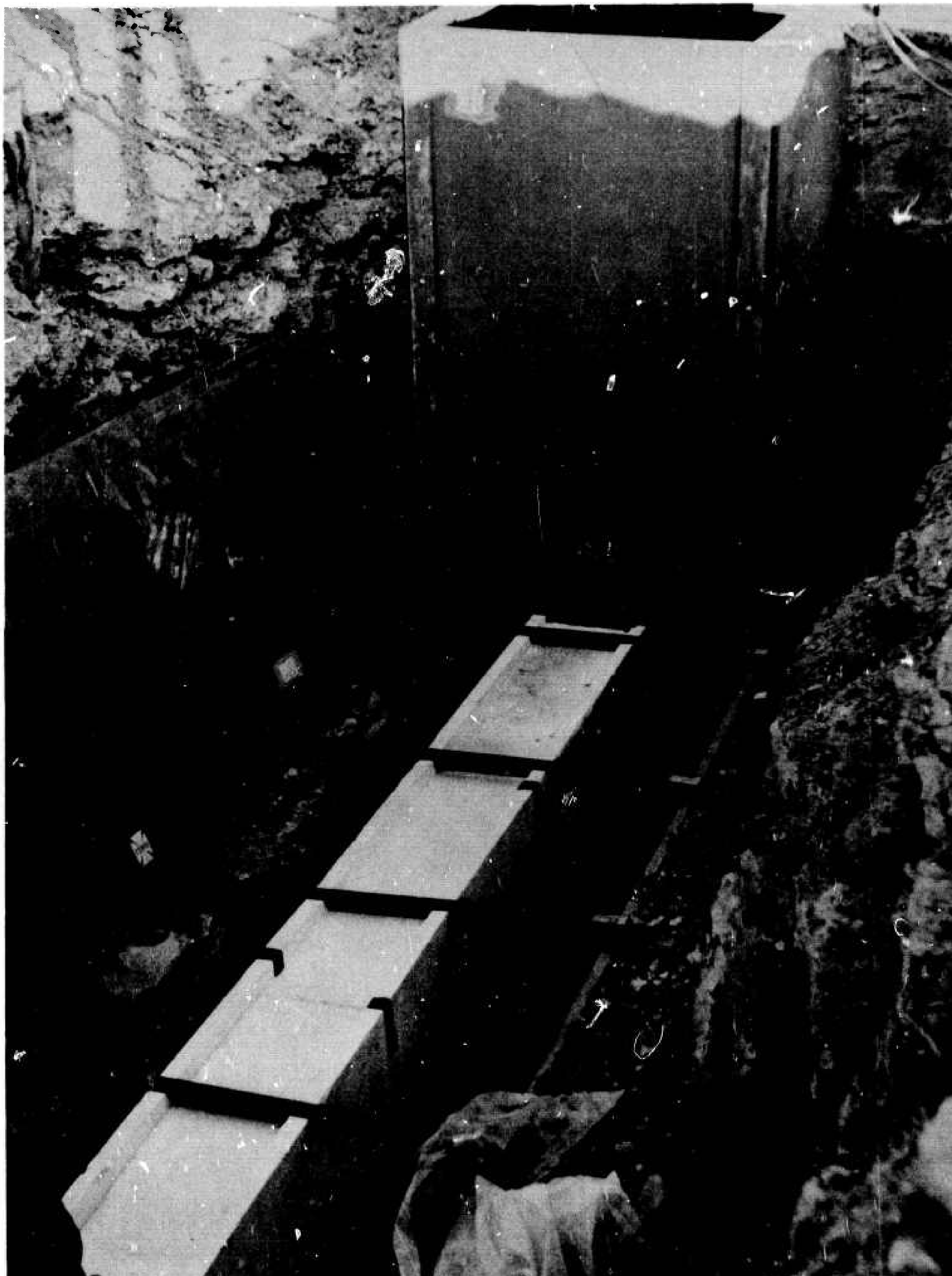

Figure 6. View of trench installation showing styrofoam insulation over the strainmeter, and showing the beams which support the culvert G 5687

3.2 MINE INSTALLATION

Mine tunnels are selected for strainmeter installations primarily to obtain a stable environment at a minimum cost. To minimize temperature instability, the mine is sealed using a steel cylinder approximately 1 meter in diameter mounted horizontally in the entrance, as shown in figure 7. The cylinder, supported by a double wall of stone and mortar, provides a hatchway that is 96.5 cm in diameter and 83.8 cm long with a gasket and cover that are held in place by bolts. A secondary door of plywood, positioned inside the hatchway, provides an air baffle to minimize air exchange when the hatchway is opened. Figure 8 pictures the hatchway at site No. 2, KP-NV, with the cover removed. Further insulation is provided by packing fiberglass between the stone walls and in the space immediately behind the hatchway cover. Direct insulating of the tube is accomplished by enclosing its length in expanded polystyrene sheets. Figure 9 shows the strainmeter in a mine prior to installation of the quartz tube and its insulation.

4. STRAINMETER

4.1 GENERAL

The strainmeter, as shown in figure 10, is composed of a 6-meter length of quartz tubing with a capacitive transducer to detect differential displacement of the end points. The quartz length standard is a single section of 45 mm (outside diameter) Thermal American Company fused quartz tubing with a glazed finish. The quartz standard is held in direct contact with an electromagnetic calibrator at the fixed end of the standard by means of a spring-loaded coupler. The calibrator is mounted on a steel anchor which in turn is secured to the bedrock with three expansion bolts. The transducer end also is secured to the bedrock by three expansion bolts. Concrete is avoided to eliminate strains induced by curing of the cement. Figure 11 is a photograph of the transducer and electromagnetic (EM) calibrator connected by a short tube, showing the relationship among the principal components of the strainmeter.

4.2 TUBE SUSPENSION

The quartz tubing is suspended by seven hangers, each containing two flexible steel straps 0.5 mm thick by 19 mm wide, by 168 mm long (figure 12). The stiffness of each suspension is approximately 2×10^4 dynes/cm. The stiffness of 6 meters of quartz tubing is approximately 5×10^9 dynes/cm. Therefore, less than 0.003 percent of the strain signal will be lost by compression of the quartz resulting from stiffness in the suspension system. The hanger straps are fastened to a rectangular frame of perforated angle iron which is bolted to the bedrock. Sheets of styrofoam 5 cm thick enclose the suspension framework and quartz tubing, as shown in figure 13.

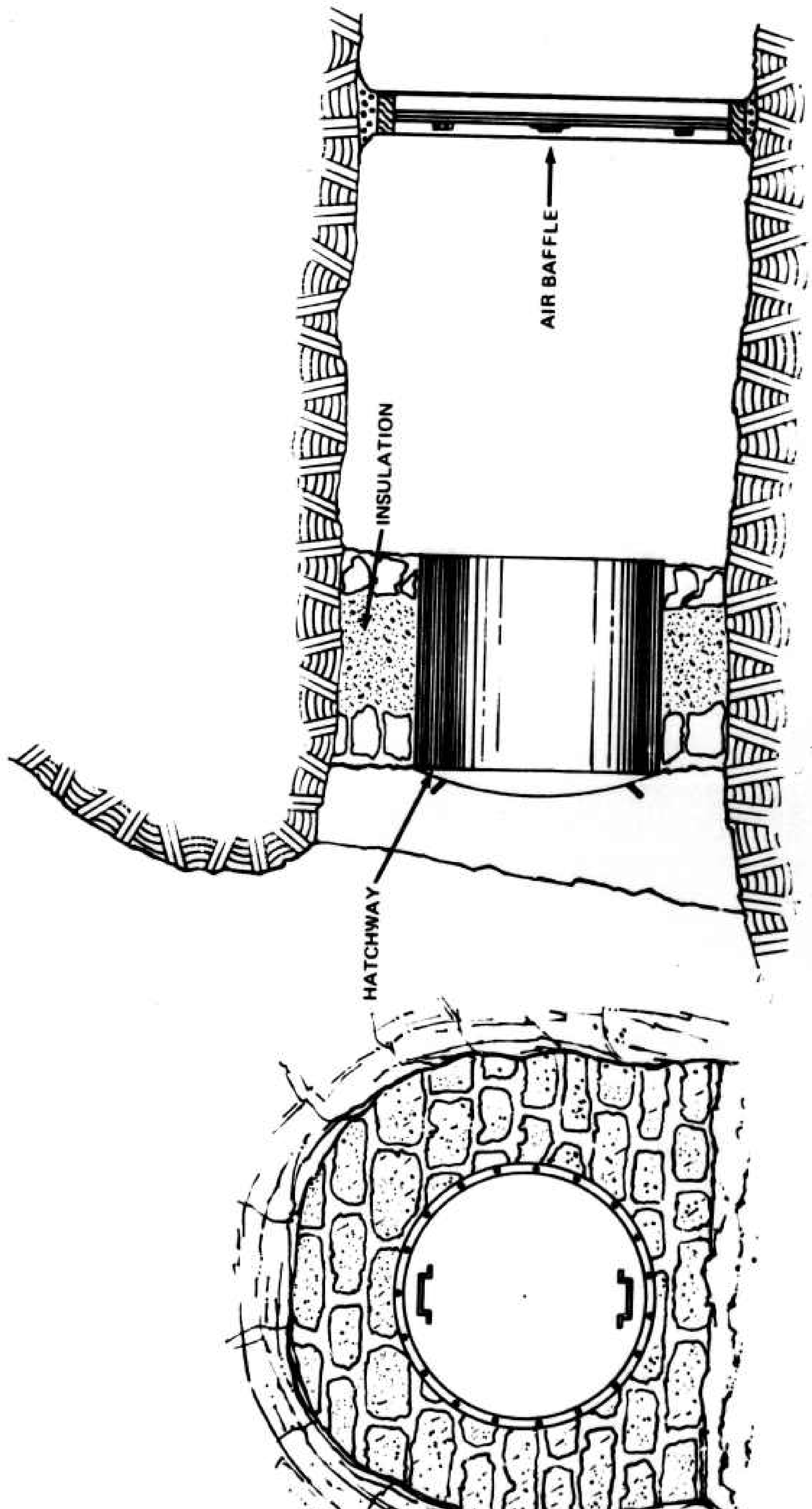

Figure 7. Cutaway view of a mine showing the insulated entrance hatch and air baffle

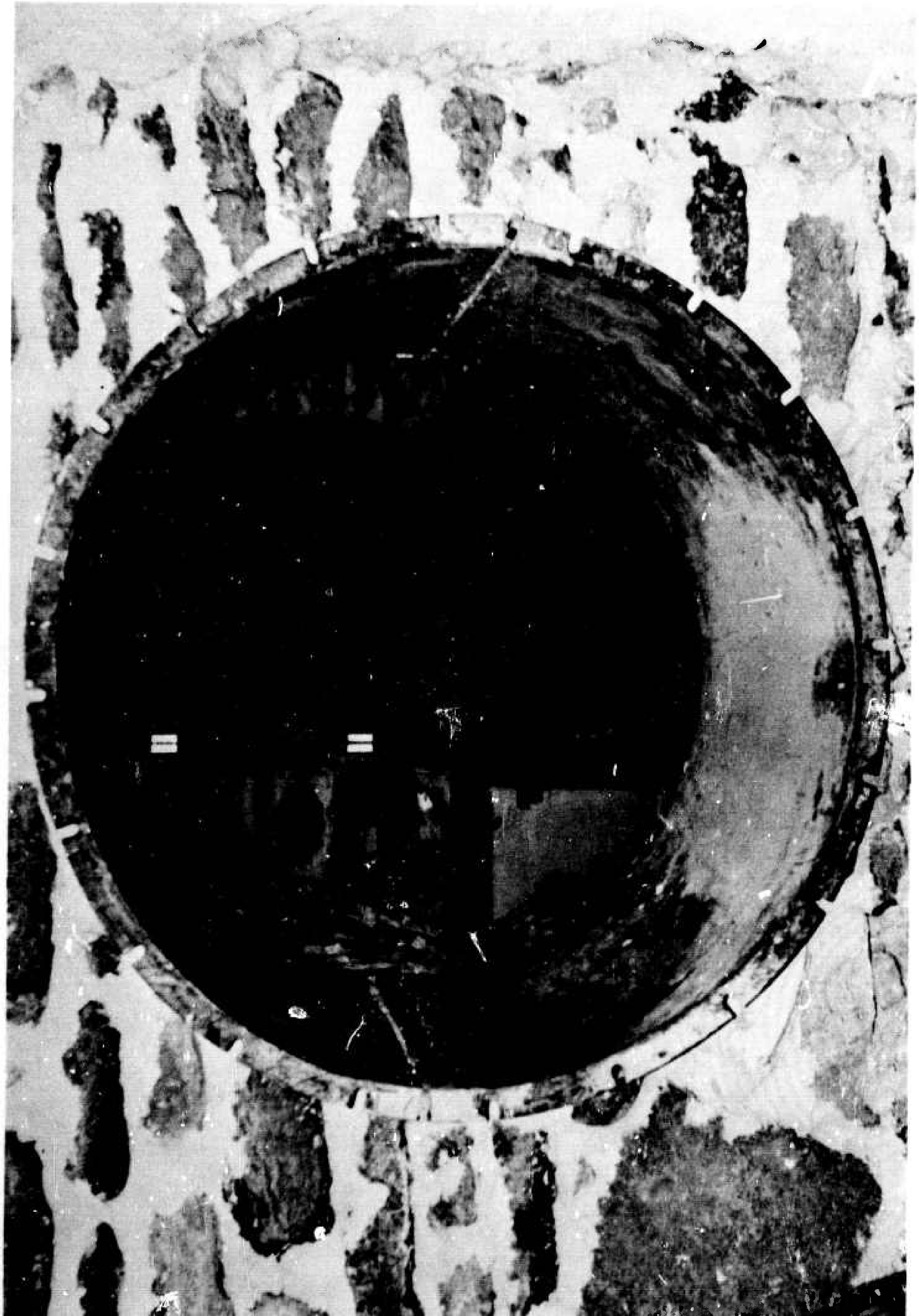

Figure 8. Photograph of entranceway at Site No. 2 (KP-NV)

G 5689

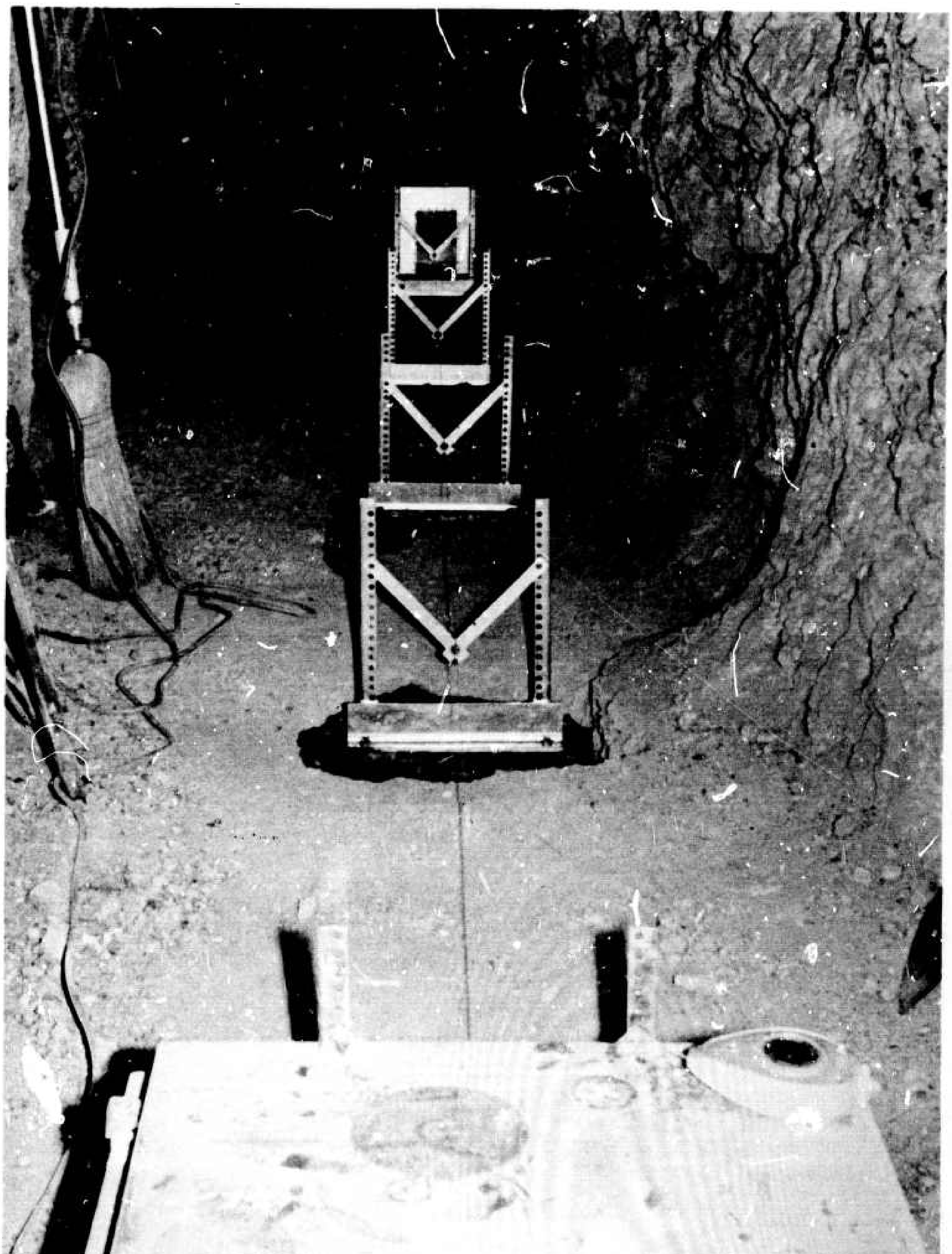

Figure 9. View of mine tunnel installation at Site No. 1 (RH-NV) before placement of quartz tubing and styrofoam insulation (view from transducer end)

G 5690

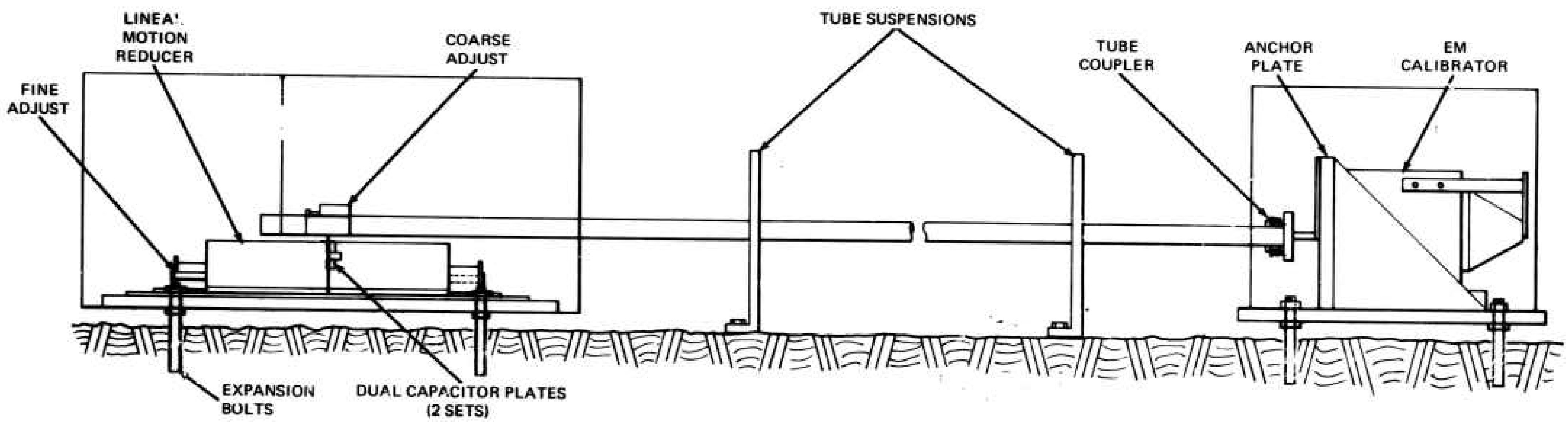

Figure 10. Sketch of strainmeter showing principal components

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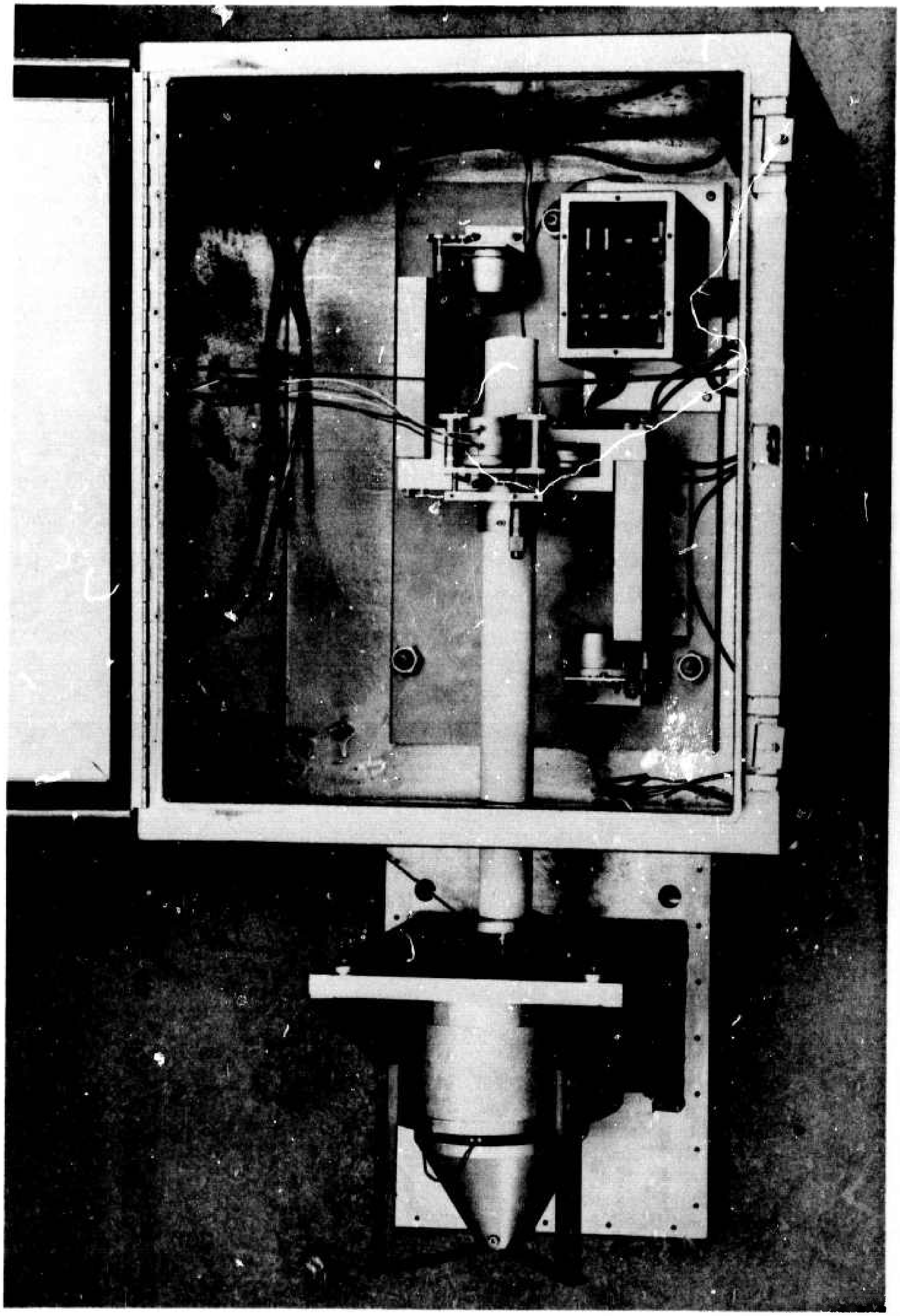

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Figure 11. Photograph of transducer and EM calibrator connected by a short tube

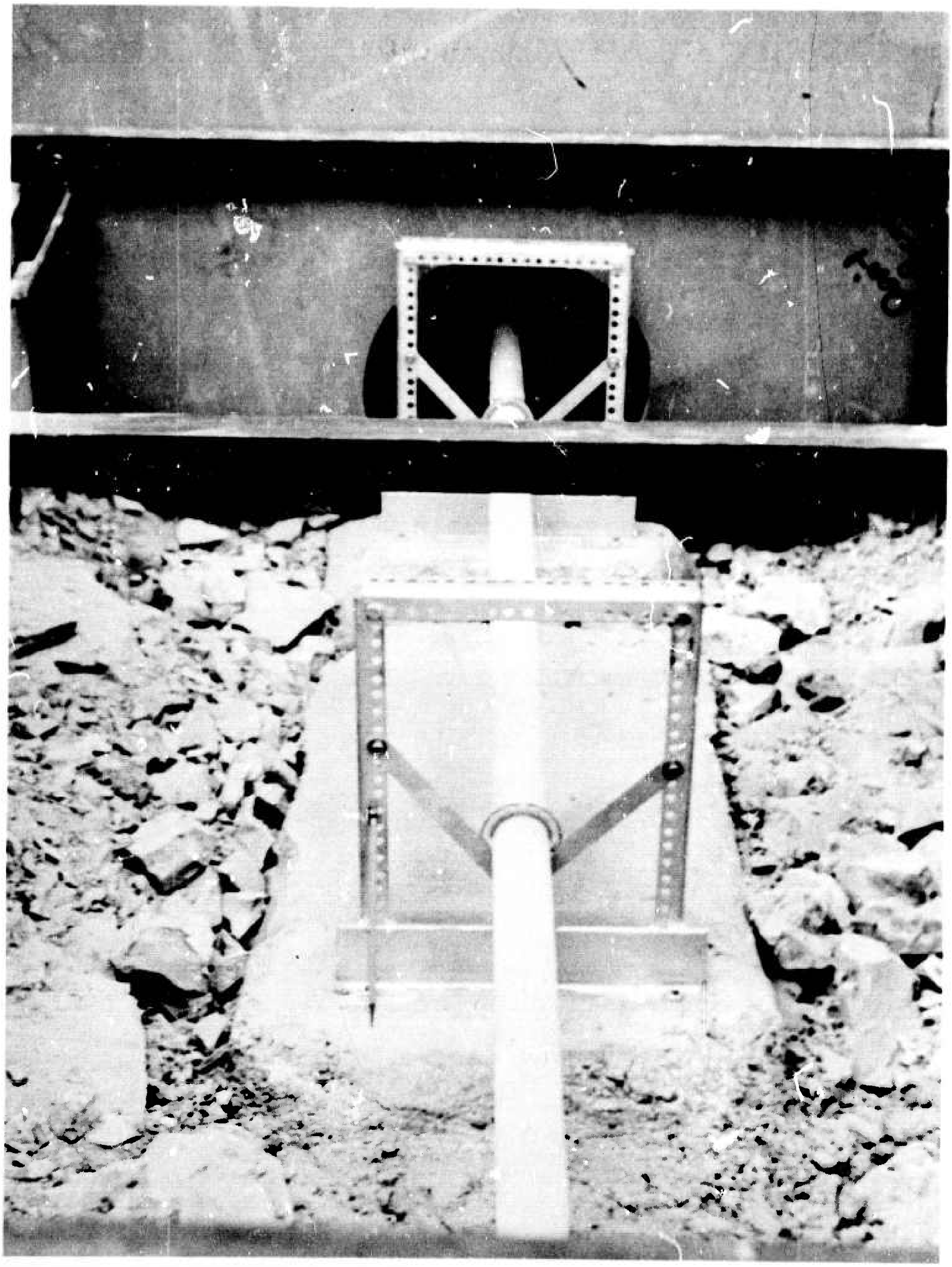

Figure 12. View of hangers suspending quartz tubing

G 5693

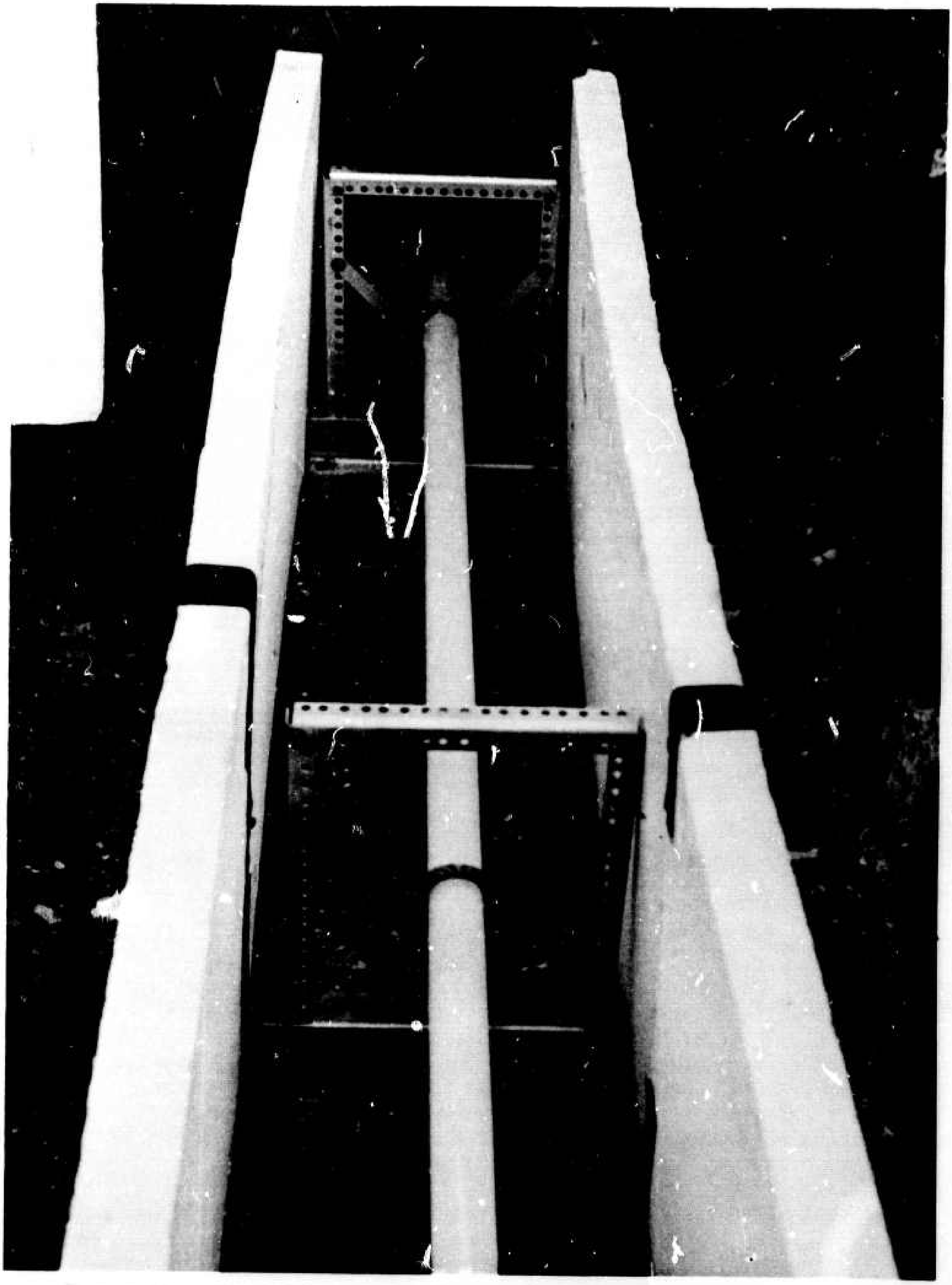

Figure 13. View of suspension framework and quartz tubing partially enclosed with styrofoam

G 5694

4.3 ELECTROMAGNETIC (EM) CALIBRATOR

The EM calibrator (figure 14) consists essentially of a coil and ring-magnet assembly which compresses or extends an 18 cm section of aluminum tubing connected to the quartz standard. The aluminum tubing is temperature compensated by a nearly equal length of aluminum rod in a foldback arrangement as shown schematically in figure 15. The theoretical calibration constant is 37.5 microns per ampere. The empirical calibration constant is 45 microns per ampere (nominal). At a practical coil current level of 3 mA and a predicted equivalent noise level of less than 3 millimicrons of differential ground displacement, less than 1 percent inaccuracy in calibration measurement is possible by averaging five cycles of calibration signal. A 0.5 percent meter is used to measure current.

4.4 VARIABLE-CAPACITANCE TRANSDUCER (VCT)

The strain transducer is of the variable capacitance type. All mechanical and electronic design features are original, with the exception of a lineal motion reducer designed in 1962 by Mr. Leonard Blayney of the California Institute of Technology. The VCT as shown in figure 11 is composed of a dual inverse capacitance (1/C) detector with the center plate attached to a coarse adjust mechanism on the free end of the quartz standard. The two outer plates are mounted on the motion reducer which in turn is fastened to a base plate bolted to the rock.

The dual capacitor with a 200-micron spacing theoretically is linear to within 0.12 percent at 10 microns displacement from center based on a stray capacitance of 25 picofarads. An additional VCT with the motion reducer reversed in direction is used to compensate for temperature effects in the motion reducer and serves as a backup transducer. The arrangement of the reducers can be seen more clearly in figure 16 in which the quartz standard, the coarse adjust unit, and the center plates have been removed. The holder for the outer plates mounted on the side of the motion reducer is also temperature compensated, since tests show that an uncompensated holder contributes more than 50 percent of the temperature drift of the transducer.

A circuit schematic of the dual 1/C detector is shown as figure 17. Each capacitor with the center plate centered has a capacitance of approximately 100 pF. Variations in pulse width are produced by variations in capacitance in each detector circuit. Pulse width differences are sensed with the use of a flip-flop circuit and an averaging filter. The dual detector has a nominal sensitivity of 40 millivolts per micron. The circuit noise, minimized by selecting Amelco 709 integrated circuits of low noise level, is less than 50 μV in the frequency range 0.001 to 1 Hz. Long-term drift occurs at a rate of 150 μV/°C. The output of two dual 1/C detectors are summed as shown in the circuit schematic of figure 18. A low-gain summation circuit is operated from the two dual 1/C detectors in parallel with the high-gain circuit. The low-gain circuit not only preserves large signals that exceed the range of the high-gain system, but serves more or less as a backup system, particularly since the two circuits are operated from different voltage regulators.

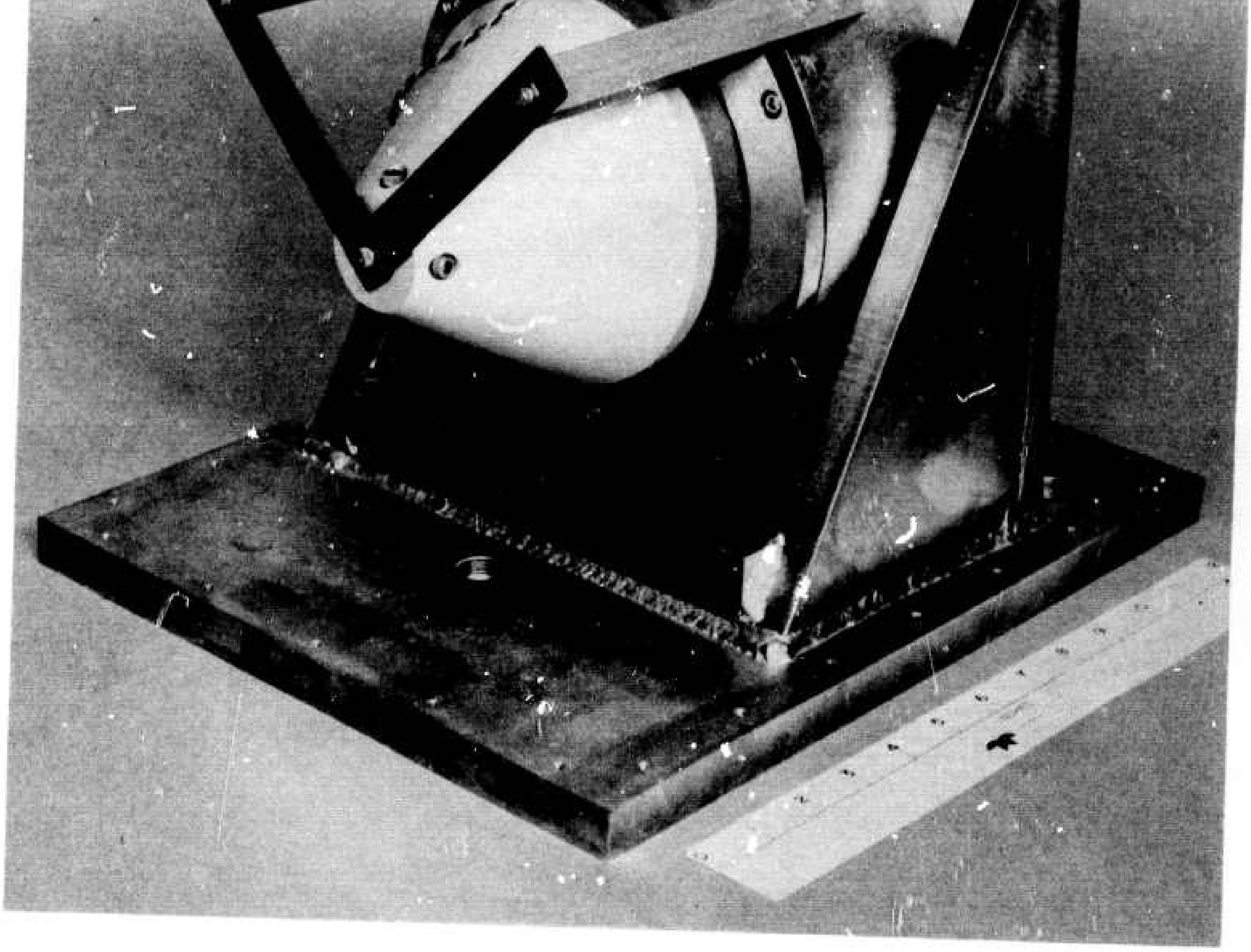

Figure 14. Photograph of EM calibrator without cover

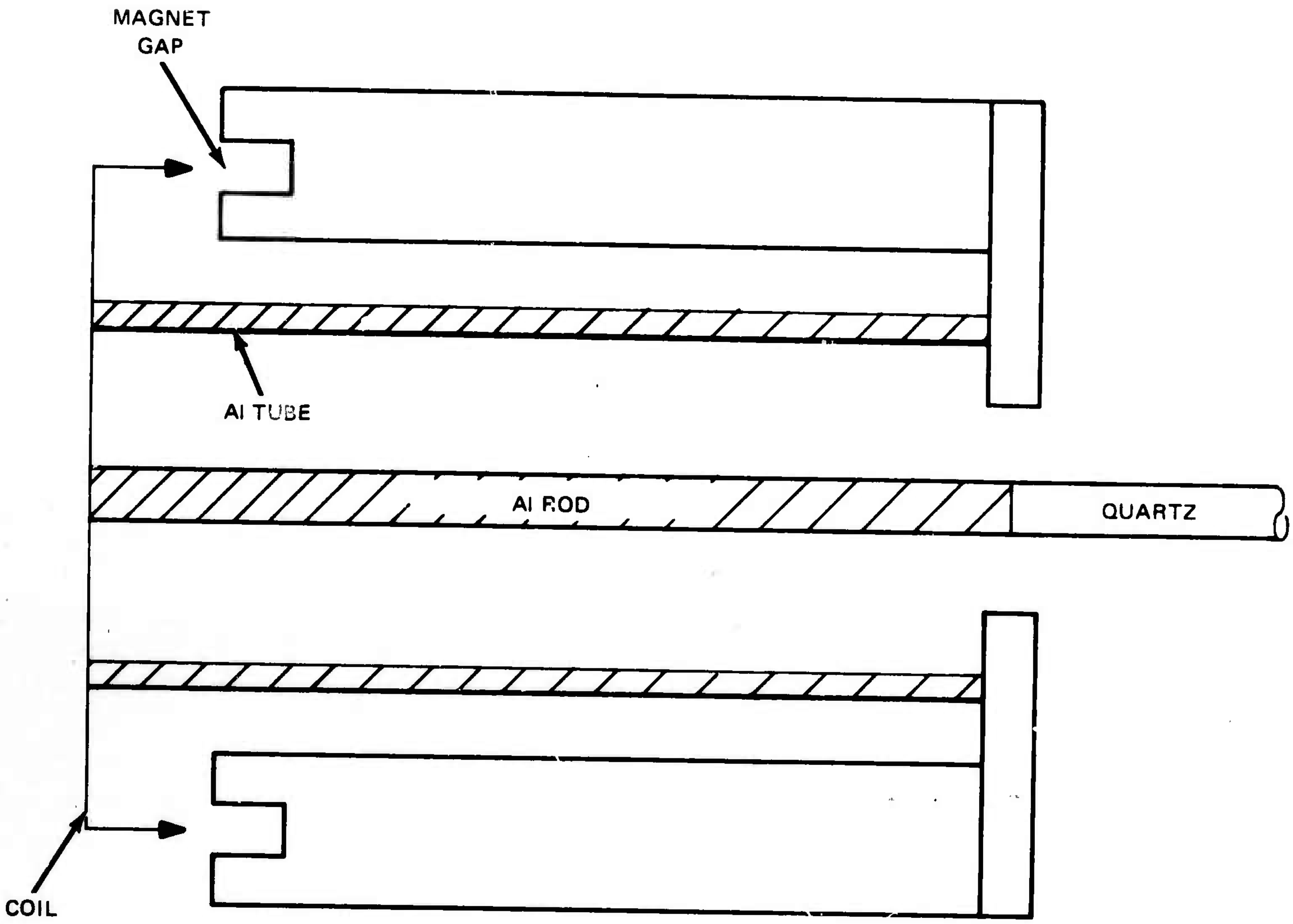

Figure 15. Schematic of temperature-compensated calibrator

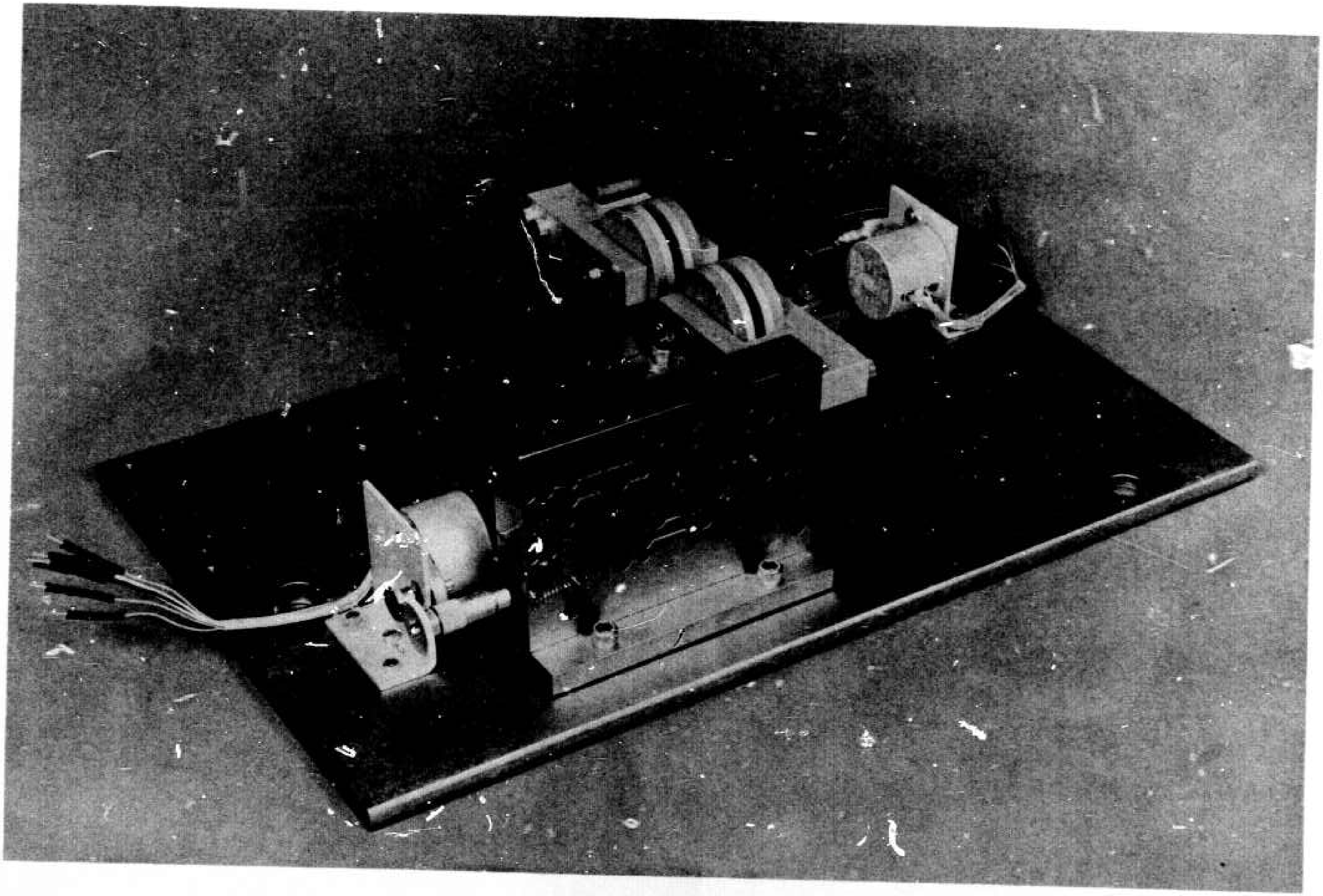

Figure 16. Photograph of VCT showing arrangement of the lineal motion reducers for temperature compensation

G 5697

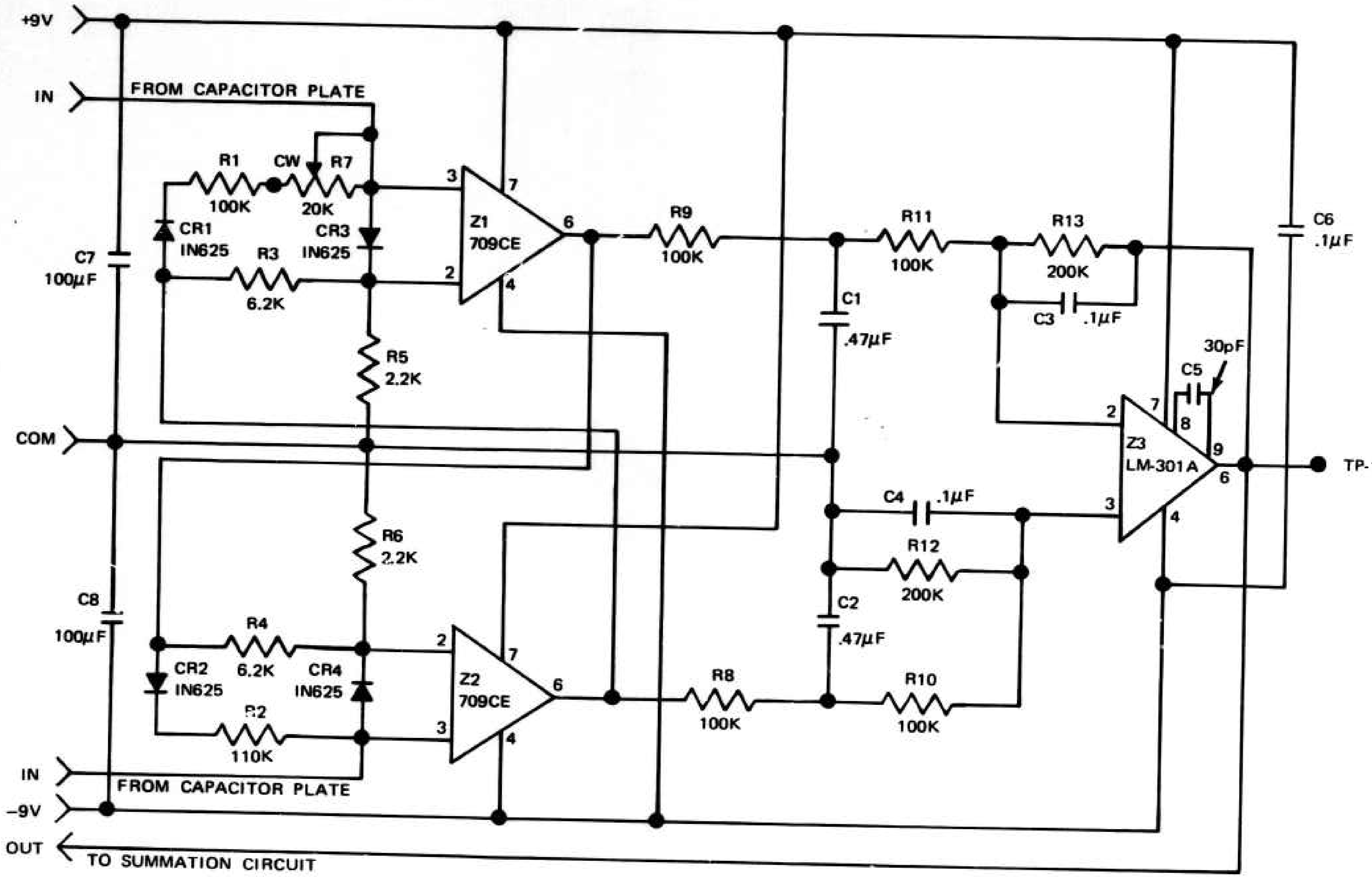

Figure 17. Circuit schematic of the dual 1/C detector

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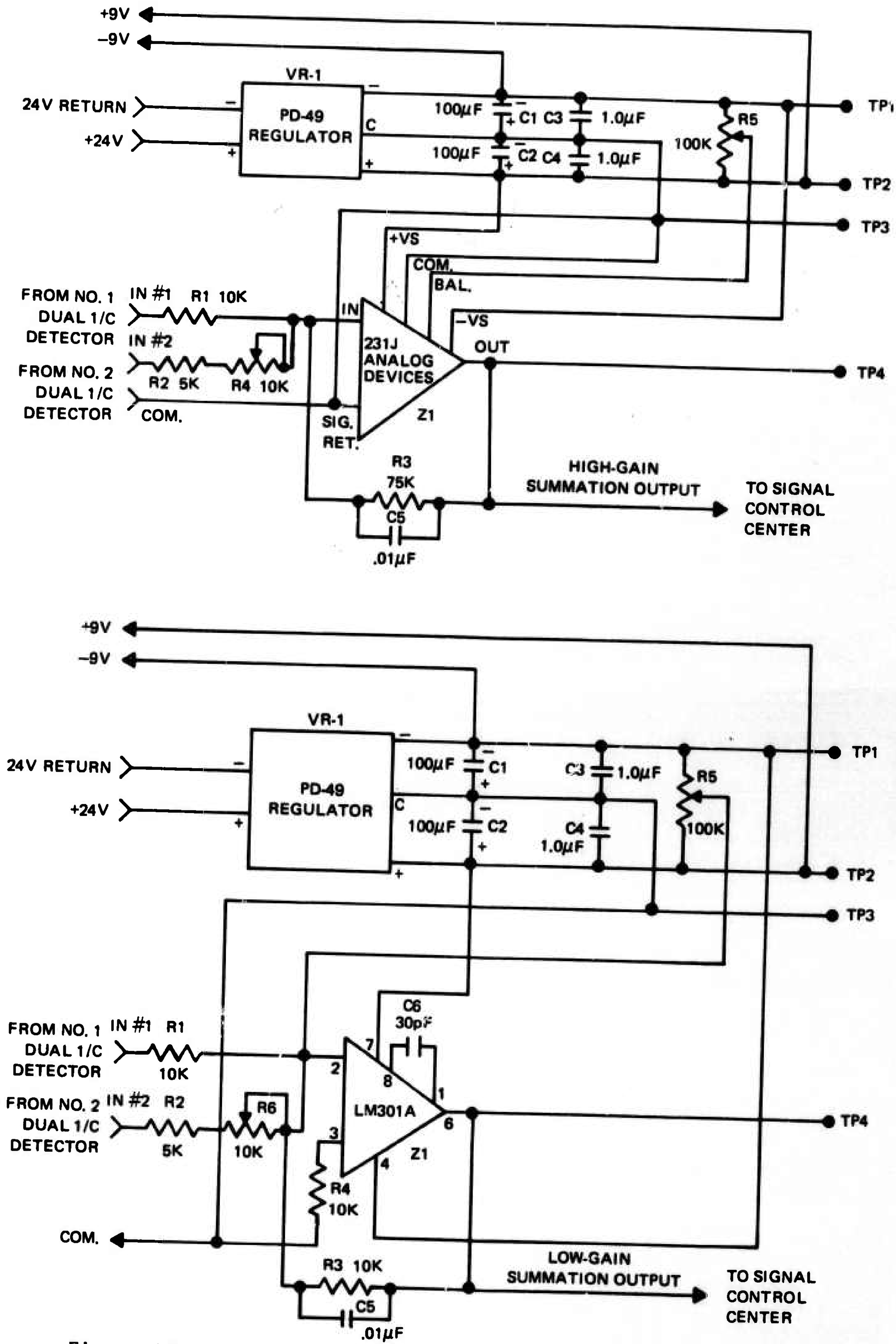

Figure 18. Circuit schematic of two dual 1/C detectors forming a high-gain and a low-gain summation circuit

G 5699

4.5 FINE ADJUSTMENT

Fine adjustment of capacitor-plate spacing is accomplished by positioning the outer plates. A stepper motor, a micrometer head, and the motion reducer form the fine-adjust mechanism (figure 19). The stepper motor rotates 1/24 revolution per step; an integral gear provides a 30:1 reduction; a pair of external gears with a reduction factor of 1.41:1 provides a lineal decoupling between motor and micrometer head; rotational motion of 0.000985 revolution per step is converted to a lineal motion of 0.493 microns per step by use of a 500-micron per revolution micrometer; the motion is then reduced by a nominal value of 100:1 in the lineal motion reducer. The reduction factor of the latter is known to an accuracy of 0.5 percent. Thus, the position of the plates is adjustable in steps of 4.93 millimicrons (nominal value) within an accuracy of 1 percent over a range of approximately 15 microns. The latter value is the operating range of the lineal motion reducer. A backlash equivalent to 13 ±3 millimicrons occurs when reversing the direction of the motor. A recording of the VCT output in response to forward and reverse steps of the fine-adjust motors during system tests in the 16.4-meter deep test facility in Garland, Texas, is shown in figure 20.

Tests show that the heating effect of the motor upon calibration accuracy is negligible. Typically, 100 steps, or 500 millimicrons, of plate displacement, will produce 100 millimicrons of heating effect on each lineal motion reducer. The heating effect will reach a peak approximately 1/2 hour after actuating the fine-adjust motor and will subside effectively in 1-1/2 hours. The temperature of the lineal motion reducer will rise 0.05 degrees centigrade per 100 steps of the motor. However, the resulting plate displacement of 0.1 micron is effectively cancelled with dual VCT's. The rate of stepping is controllable by applying voltage pulses to the motors from a function generator through a logic circuit. By operating the function generator at 40 Hz and then switching the frequency band to reduce the switching rate, the outer plates of the detector can be displaced over the full range of the fine-adjust mechanism (15 microns or approximately 3000 steps) in less than 90 seconds, before the heating effect can affect the accuracy of the calibration.

4.6 COARSE ADJUSTMENT

The coarse-adjust mechanism (figure 21) displaces the central capacitor plate of both VCT's simultaneously. A stepper motor and micrometer head provide a predicted displacement sensitivity of 0.35 micron per step. A backlash of approximately 1.0 micron occurs when the motor is reversed. The coarse adjust unit is designed to center the central plate during initial installation to avoid consuming the adjustment range of the fine-adjust unit. It also may be necessary to actuate the coarse adjust to counteract seasonal temperature change in near surface tunnels and in the trench installations. A record showing operation of the coarse adjust unit in laboratory tests is shown in figure 22. A backlash of 1.4 microns is evident in that unit. Note also the apparent difference in accumulated plate displacement between forward and reverse motion.

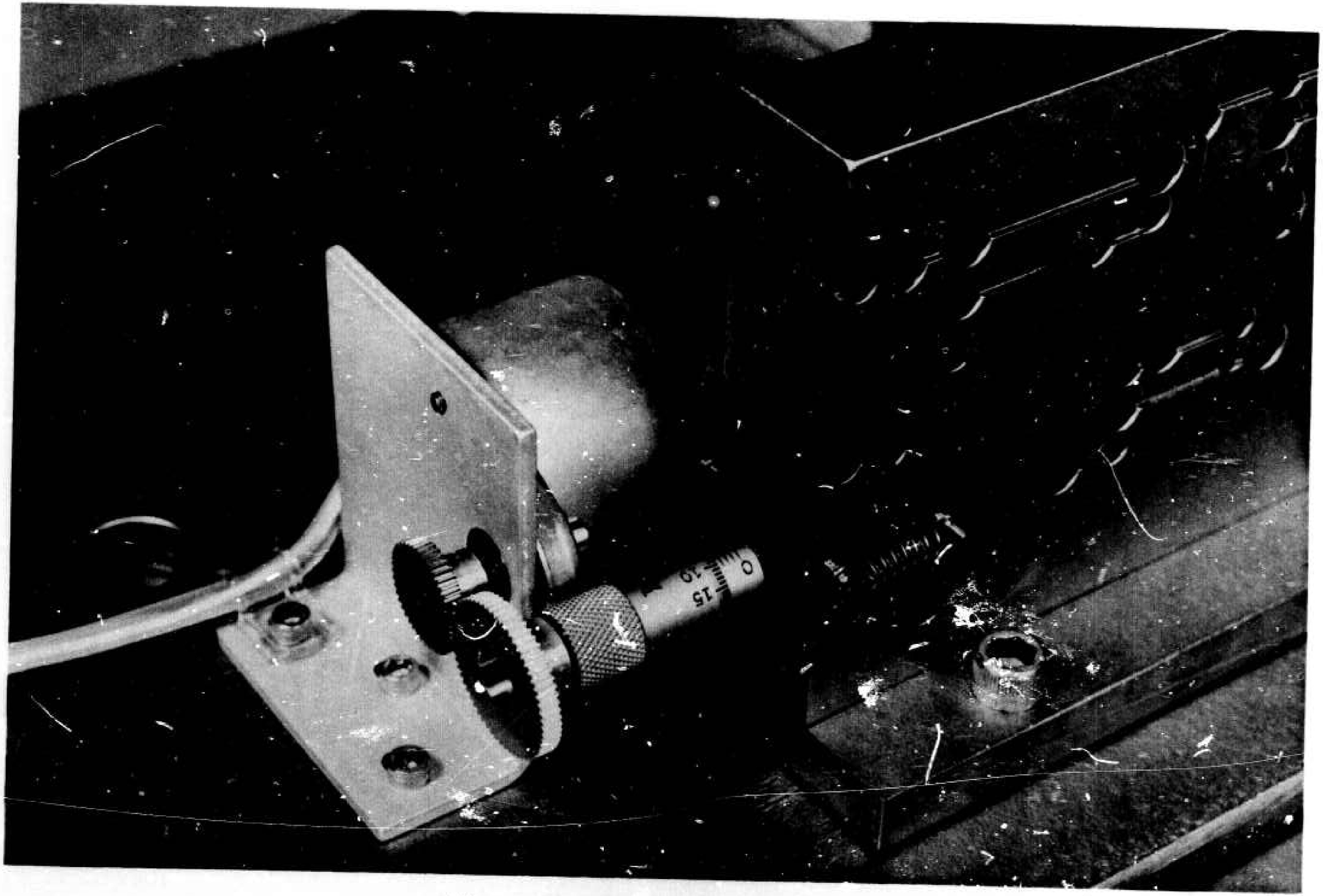

Figure 19. Fine-adjust mechanism

G 5700

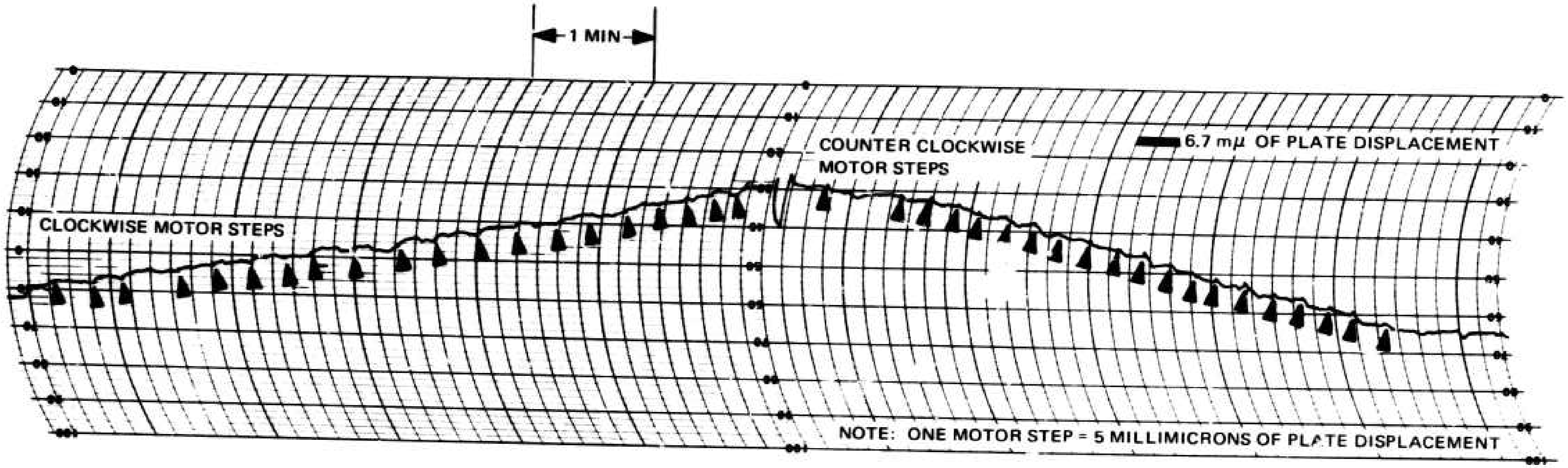

Figure 20. Recording of 20 forward steps and 20 reverse steps of fine-adjust mechanism on variable-capacitance transducer operating in 16.4-meter deep test shaft in Garland, Texas

G 5701

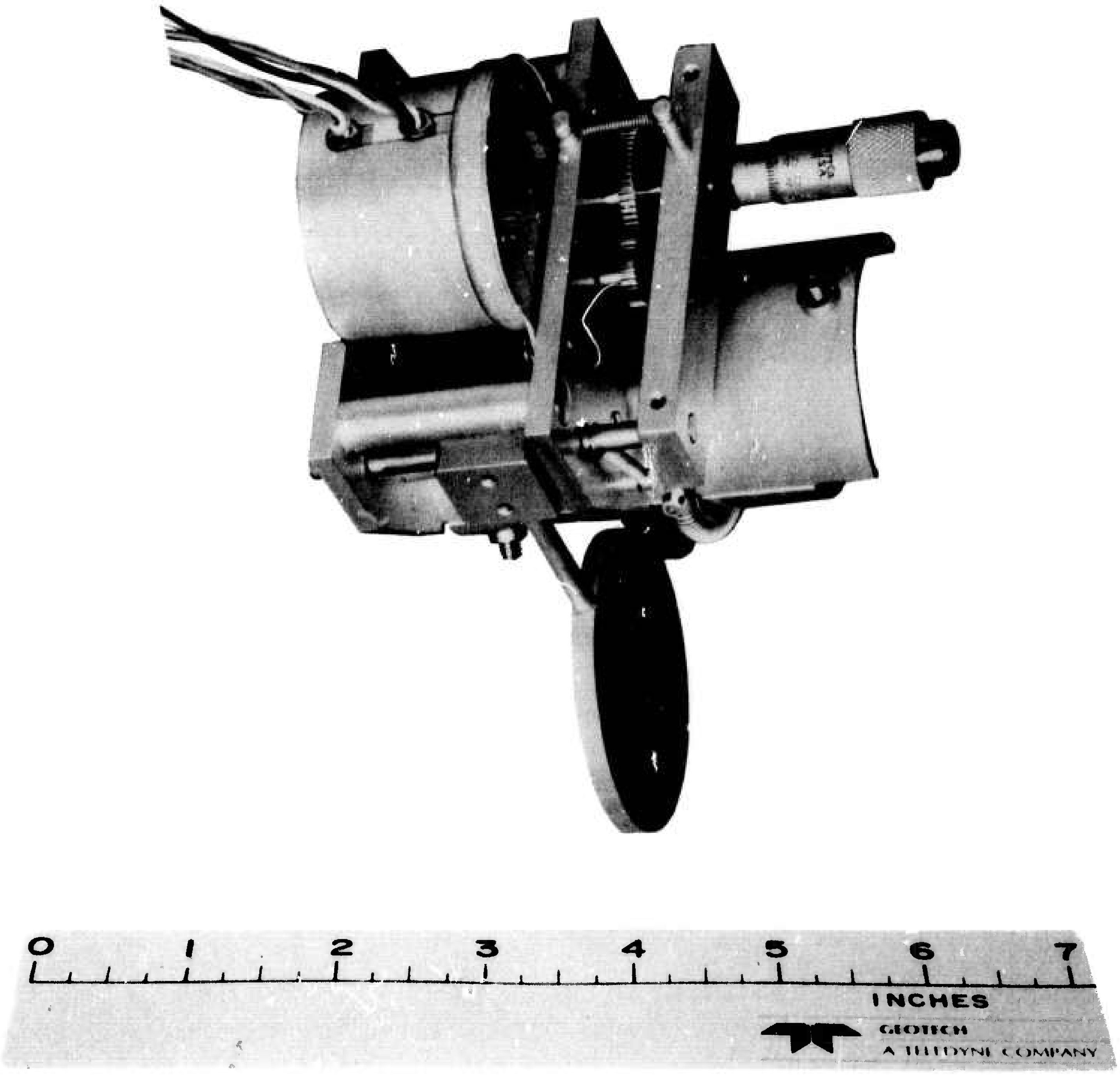

Figure 21. Coarse-adjust mechanism

G 5702

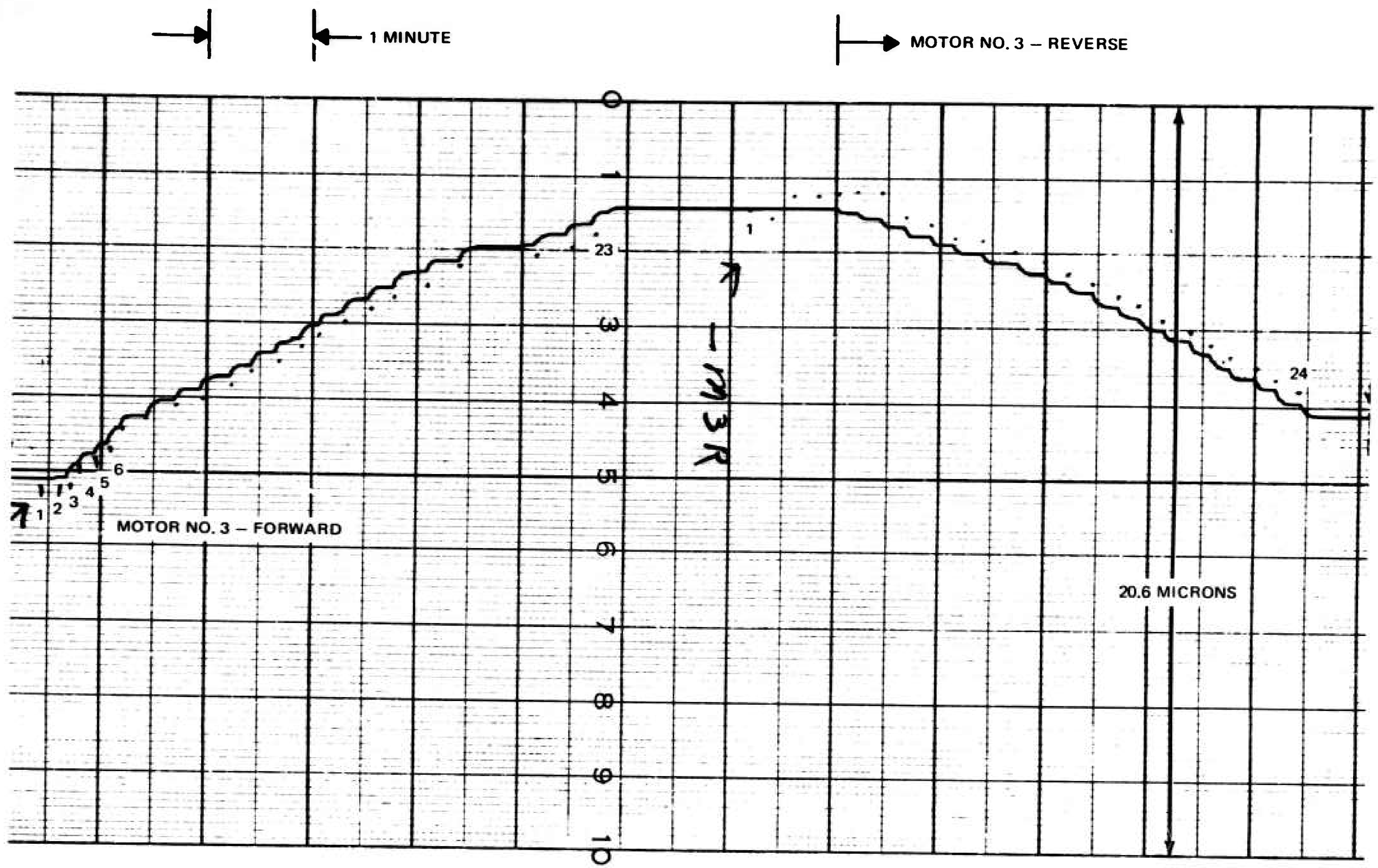

Figure 22. Record showing operation of coarse adjust unit in laboratory. Motor steps are numbered. The predicted plate displacement for each step is 0.35 microns

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5. SIGNAL CONTROL CENTER

The Signal Control Center (SCC), shown in figures 23 and 24, contains an optional gain amplifier and an active filter in both the primary (high gain) strain and the secondary (low-gain) strain channels, and contains a bridge circuit for the high resolution (0.001°C) temperature channel. The environmental channel, radio channel, and power for the magnetic tape recorder and the radio are wired through the SCC.

Normally, a signal control center houses only operational amplifiers and components that control the frequency response and gain of a system. However, an important feature of the SCC for the portable strain system is a voltage control circuit which maintains the signal level within the dynamic range of the magnetic tape channels. Two such circuits are available in the SCC -- one for the primary (high-gain) strain channel, and one for the high-gain temperature channel.

The voltage control circuit in figure 23, consists basically of a DAC amplifier; a precision voltage level detector; a logic circuit that detects pulse increments from the level detector and controls the switching of a 12-bit ladder in the D to A converter; and a voltage reference regulator for the ladder. Specifically, data are applied to the DAC amplifier summing network which contains an operational amplifier with a gain of 8. The level detector at the output of the DAC amplifier is triggered at a level of 1.32 volts. Each 1.32-volt increment is sensed by a logic circuit and undergoes a D to A conversion in a 12-bit ladder network which has a least significant bit of 2.5 millivolts. An incremental voltage in the opposite polarity is fed back to the DAC amplifier summing network, reducing the DAC amplifier output to 0 ±20 millivolts in response to the 1.32-volt triggering of the level detector. Thus, by the foregoing offset biasing technique, the voltage control circuit maintains the output signal within a dynamic range of 50 dB for an input signal of 66 dB. The number and polarity of the offset increments are recorded on a separate track of the tape recorder for restoration of the input signal.

The offset bias signal from the DAC is a 0-50 Hz sawtooth wave. The ultimate limitation on repetition rate of the offset bias signal is the tape recorder which has a 5 Hz cutoff in the FM channels containing strain and temperature data and a 50 Hz cutoff in the "DIRECT RECORD" channels containing the offset counts.

The initial design plan for the DAC called for use of a 14-bit ladder. A compromise between optimum design and delivery schedule resulted in the use of a 12-bit ladder. As a consequence the lesser dynamic range of the system with the 12-bit ladder forces a resetting of capacitor plates when secular strains displace the capacitor plates more than 3 microns, thus limiting loss of dynamic range of the voltage control circuit to 6 dB.

The voltage control circuit is aligned with a digital voltmeter by adjusting the reference voltage to 10.24 volts ±2.5 millivolts; the detector level to 1.32 volts ±10 millivolts; and all dc balance adjustments to zero ±10 millivolts. The minimum resolvable signal at the input to the DAC amplifier is ±5 millivolts. The maximum signal is ±10 volts.

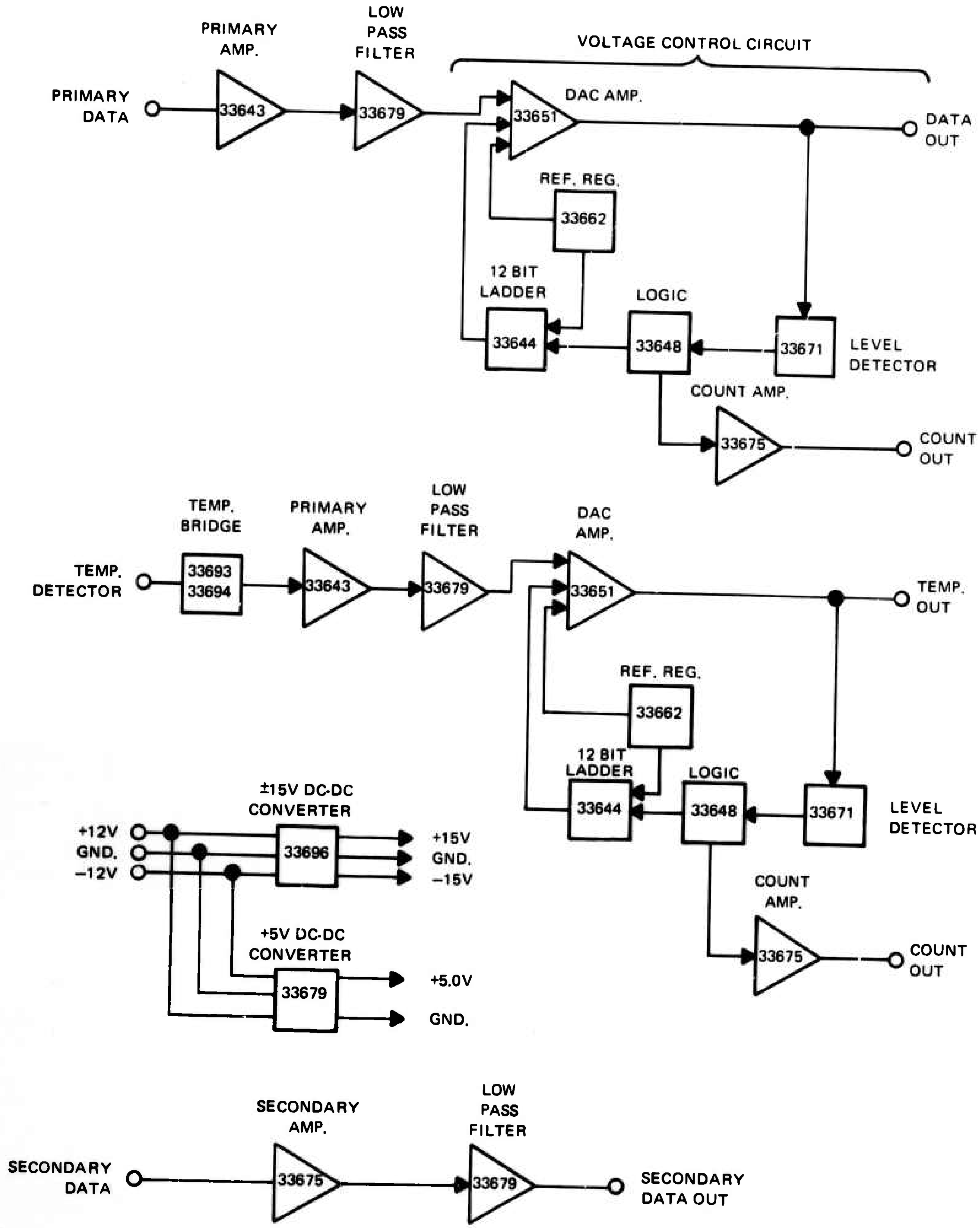


Figure 23. Block diagram of signal control center

G 5704

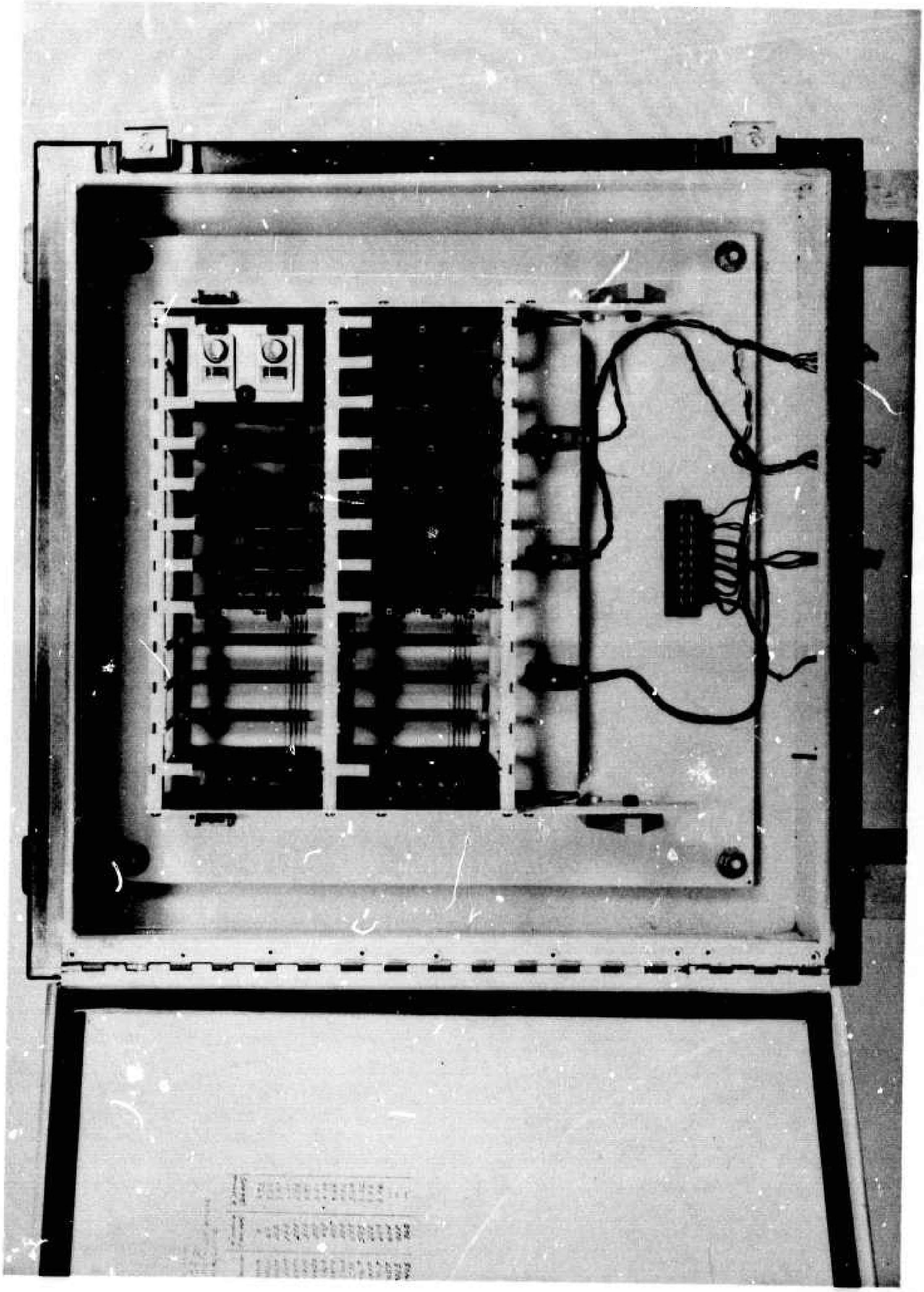


Figure 24. Photograph of signal control center. Extra connectors allow for expansion to a 14-bit DAC

A system block diagram of strain channel components and gain levels is shown in figure 25. In the high-gain strain channel, an optional gain card with a gain of X4 provides a strain resolution of 5×10^{-10} limited by electronic noise in the detector. This signal is approximately 6 dB above the noise level of the magnetic tape recorder channel. Optional gain cards in 6 dB increments permit operation at lower gains when environmental strains create a practical limit to system sensitivity. The maximum useful strain sensitivity for the portable strain system is a nominal 1.1 volt per 1×10^{-8} strain.

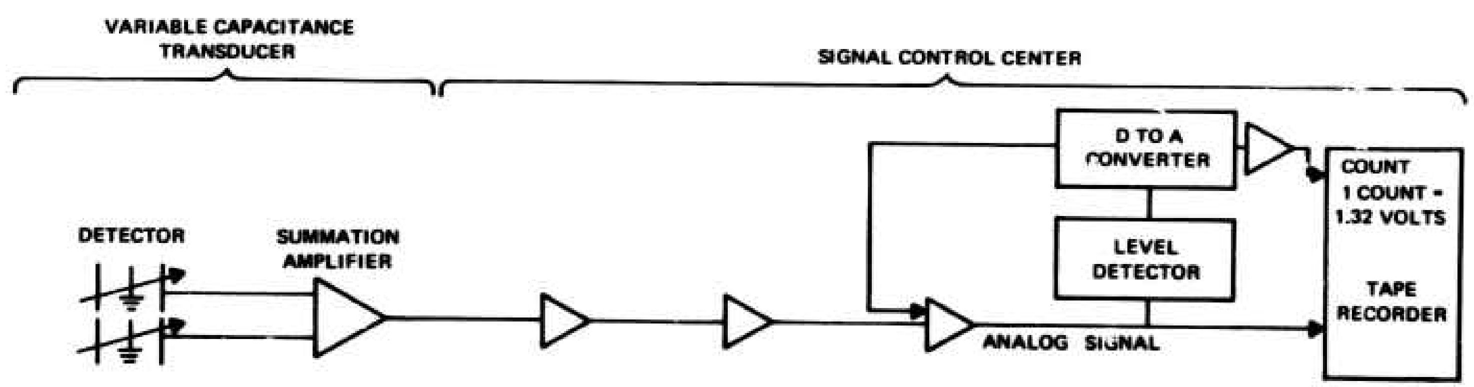
6. ENVIRONMENTAL DATA UNIT

The four-channel environmental data unit (figure 26) consists of three active networks and one passive network the outputs of which are time shared by means of an automatic sequential output selector. The three active networks measure temperature with a resolution of 0.01°C, 0.1°C, and 1°C at the linear motion reducer in the strain transducer enclosure, in the transducer vault, and in the outside air, respectively. Each active channel contains a thermistor, a bridge network, and an operational amplifier the output of which is single ended and referenced to a power common of a +9, common, -9 volt regulator. Each channel has 13 ranges with midpoints at 1-degree increments from 10°C to 22°C. The 0.01°C, 0.1°C, and 1 C° channels have a sensitivity of 4 V/°C, 0.4 V/°C, and 0.04 V/°C, respectively. The fourth network accepts the output from a meteorological instrument such as an anemometer, a microbarograph, or a pyrheliometer, and routes it directly to the sequential selector. The duration of the signal is 88 seconds for channels 1 through 3, and 66 seconds for channel 4. No output is registered for 2 seconds following the signals from channels 1, 2, and 3, and 10 seconds following the signal from channel 4. The power requirement is 24 Vdc at 68 mA and 12 Vdc at 4 mA. A photograph of the environmental data unit is shown as figure 27.

The temperature networks were tested over a period of several weeks in conjunction with development of the strain transducer in the 16.4-meter deep test shaft in Garland.

7. TIME CODE RECEIVER

The Time Code Receiver, Specific Products, Model T-60A, operating on a frequency of 60 kHz, receives the BCD time code transmitted continuously from station WWVB (Boulder, Colorado). The time code contains information on minutes, hours, and day of the year, and the difference in milliseconds between the time as broadcast and the best known estimate of UT2 (Uniform Time). A photograph of the receiver is shown as figure 28.



	STRAIN	DIFFERENTIAL DISPLACEMENT (meters)	DETECTOR SENSITIVITY (v/m)	SUMMATION CIRCUIT GAIN	OPTIONAL AMPLIFIER GAIN	FILTER GAIN	DAC AMPLIFIER GAIN	SIGNAL LEVEL IN DAC (volts)	SIGNAL LEVEL AT INPUT TO TAPE RECORDER (volts)
PRIMARY (HIGH-GAIN) CHANNEL									
Minimum resolvable strain (center-to-peak)	5×10^{-10}	3×10^{-9}	40×10^{3}	15	4	1	8	0.0576	0.0576
Maximum strain	6.95×10^{-7}	4.17×10^{-6}	40×10^{3}	15	4	1	8	80	1.32
SECONDARY (LOW-GAIN) CHANNEL									
Minimum resolvable strain***	5.83×10^{-8}	0.35×10^{-6}	40×10^{3}	2	1	1	—	—	0.028
Maximum strain****	2.92×10^{-6}	17.5μ	40×10^{3}	2	1	1	—	—	1.4

* LIMITED BY NOISE IN THE DETECTOR CIRCUIT
** LIMITED BY THE RANGE OF THE DIGITAL TO ANALOG CONVERTER IN THE VOLTAGE CONTROL CIRCUIT
*** LIMITED BY TAPE NOISE
**** LIMITED BY THE DYNAMIC RANGE OF THE TAPE RECORDER

Figure 25. System block diagram of strain channel components and chart of minimum resolvable and maximum strain levels for the high-gain and the low-gain strain channels

G 5706

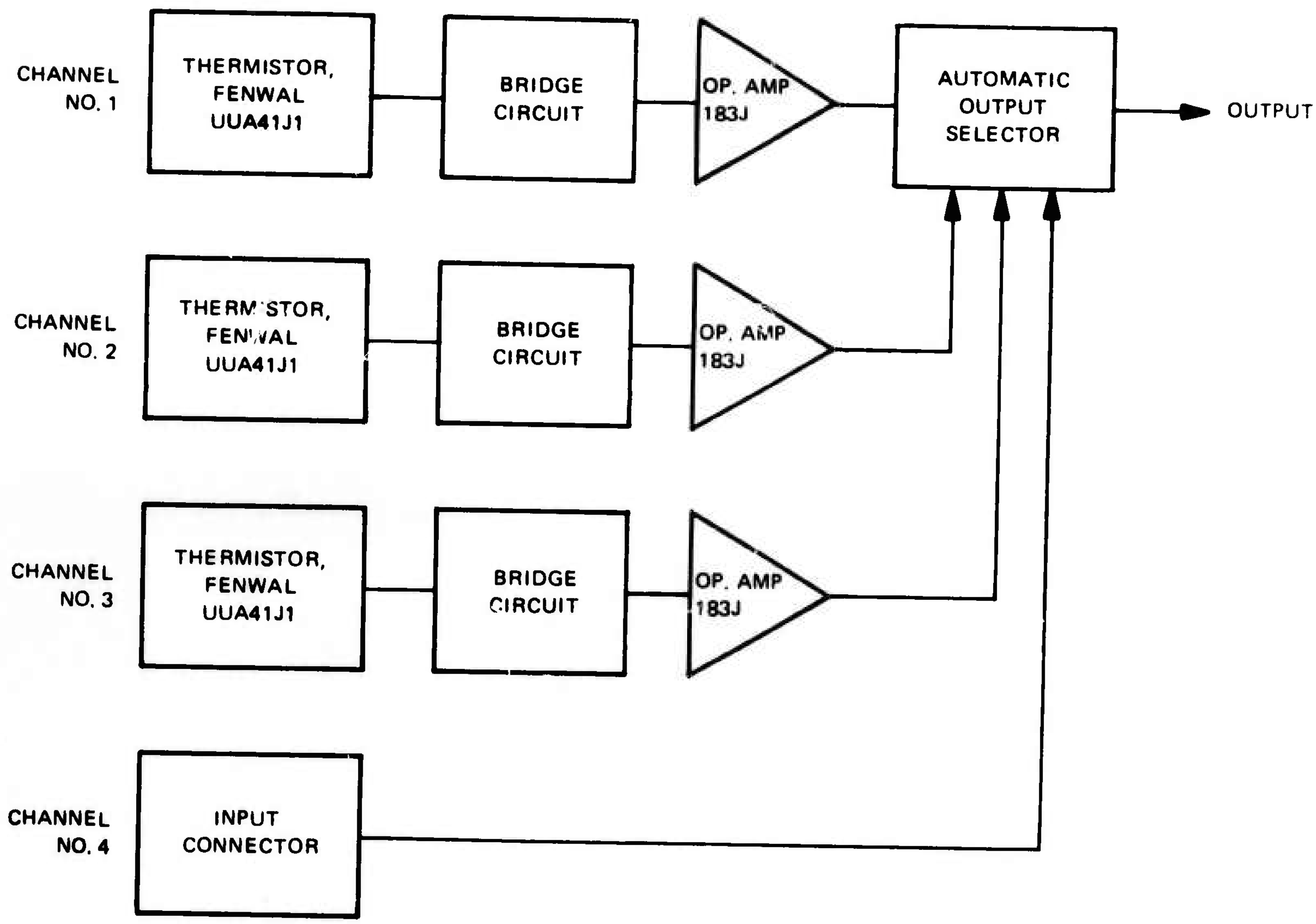


Figure 26. Block diagram of environmental data unit

G 5707

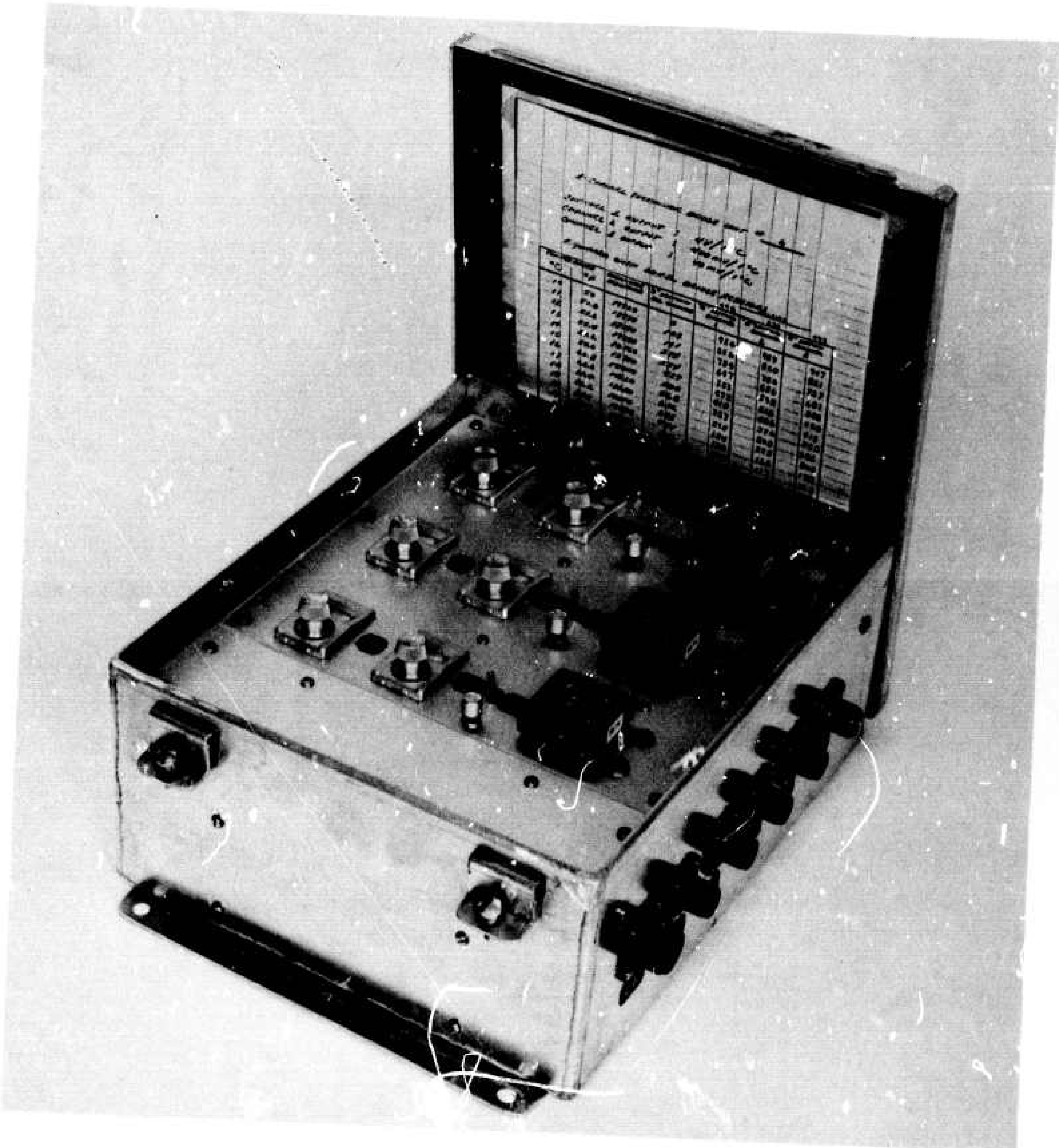


Figure 27. Photograph of environmental data unit

G 5708

Figure 28. Photograph of Time Code Receiver, Specific Products Model CS-60-P

8. MAGNETIC TAPE RECORDER

All data will be recorded on a Geotech Model 17373 magnetic tape recorder (Figure 29) which contains seven channels (IRIG) and records data on 1/2-inch tape at a speed of 0.03 inch per second. The maximum duration of recording per reel is 33-1/3 days. One playback channel is available for monitoring recorded data from any of the seven channels without interrupting the recording process. A stepper motor mounted on the channel selector switch (figure 30) permits remote selection of channel to be monitored.

9. RECORDING FACILITY

The recording facility, as shown in figure 31, consists of a prefabricated hut and an insulated subsurface enclosure which houses the signal control center, the tape recorder, an environmental data unit, and a time code receiver. The recording facility is designed to maintain diurnal temperature change in the instrument enclosure within 5 centigrade degrees. The 5-degree specification is based on the need to control the voltage drift within 70 millivolts per day. The plywood instrument enclosure which is 60 cm deep x 90 cm wide x 120 cm long is set 45 cm deep with 15 cm extending above ground level, as shown in figure 32. The size of both the enclosure and the hut is adequate for test work and maintenance of the instruments. A photograph of the hut used in system tests is shown as figure 33. A junction box mounted on the front of the PTA hut contains input and output connectors, as well as current overload and high voltage protection for data input, monitoring, tape reproduce, calibration, motor control, and power lines that are routed through the box. A photograph of the junction box is shown as figure 34.

10. SERVICE INSTRUMENTATION

Two LRSM four-wheel drive 3/4-ton GMC pickup trucks with enclosures on the rear section have been equipped as service vehicles. Each truck can service at least three widely separated portable strain sites in the array on a routine basis -- supplying propane and performing routine calibration and monitoring of system operation. Each vehicle contains the following service equipment:

a. A cable 10 meters in length to connect the control equipment in the service vehicle to the junction box at the recording facility;

b. A control panel for calibration and for control of stepper motors and switches;

c. Two 12-volt lead acid storage batteries which furnish power to the control panel, a function generator, and an inverter for operating an oscilloscope;

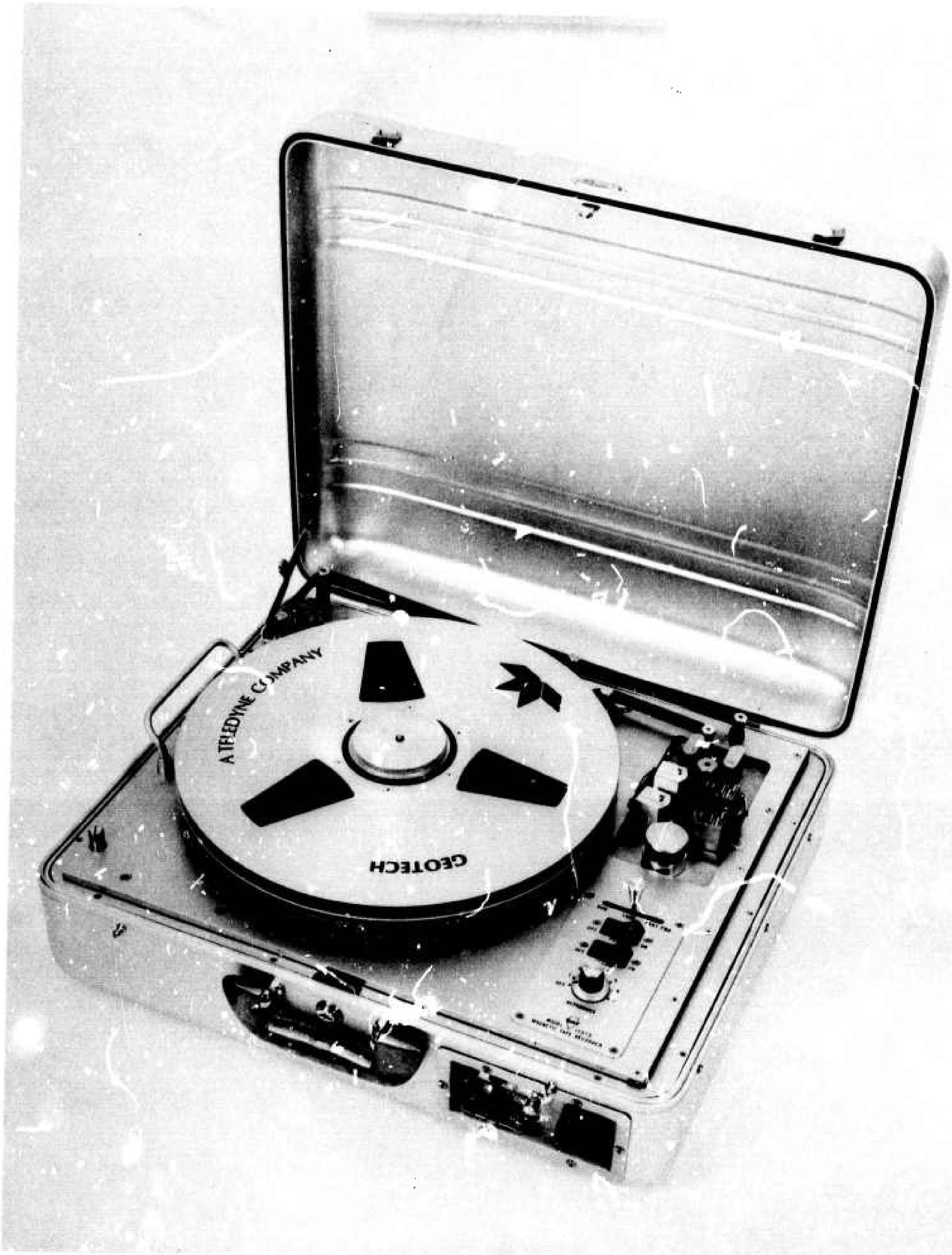


Figure 29. Photograph of Geotech Model 17373 magnetic tape recorder

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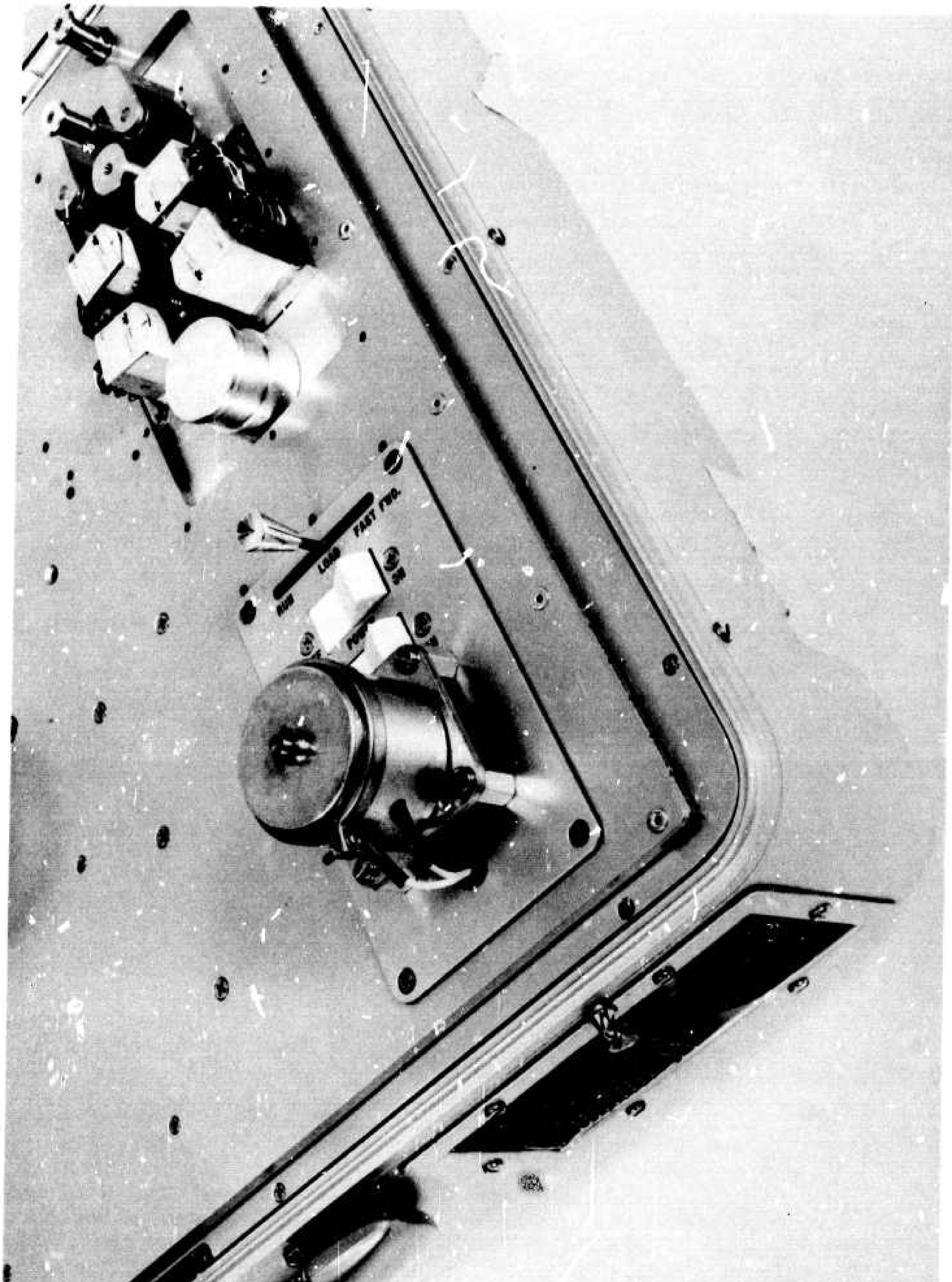

Figure 30. Photograph of recorder modification showing the stepper motor mounted on channel selector switch which permits remote selection of channel to be monitored

G 5711

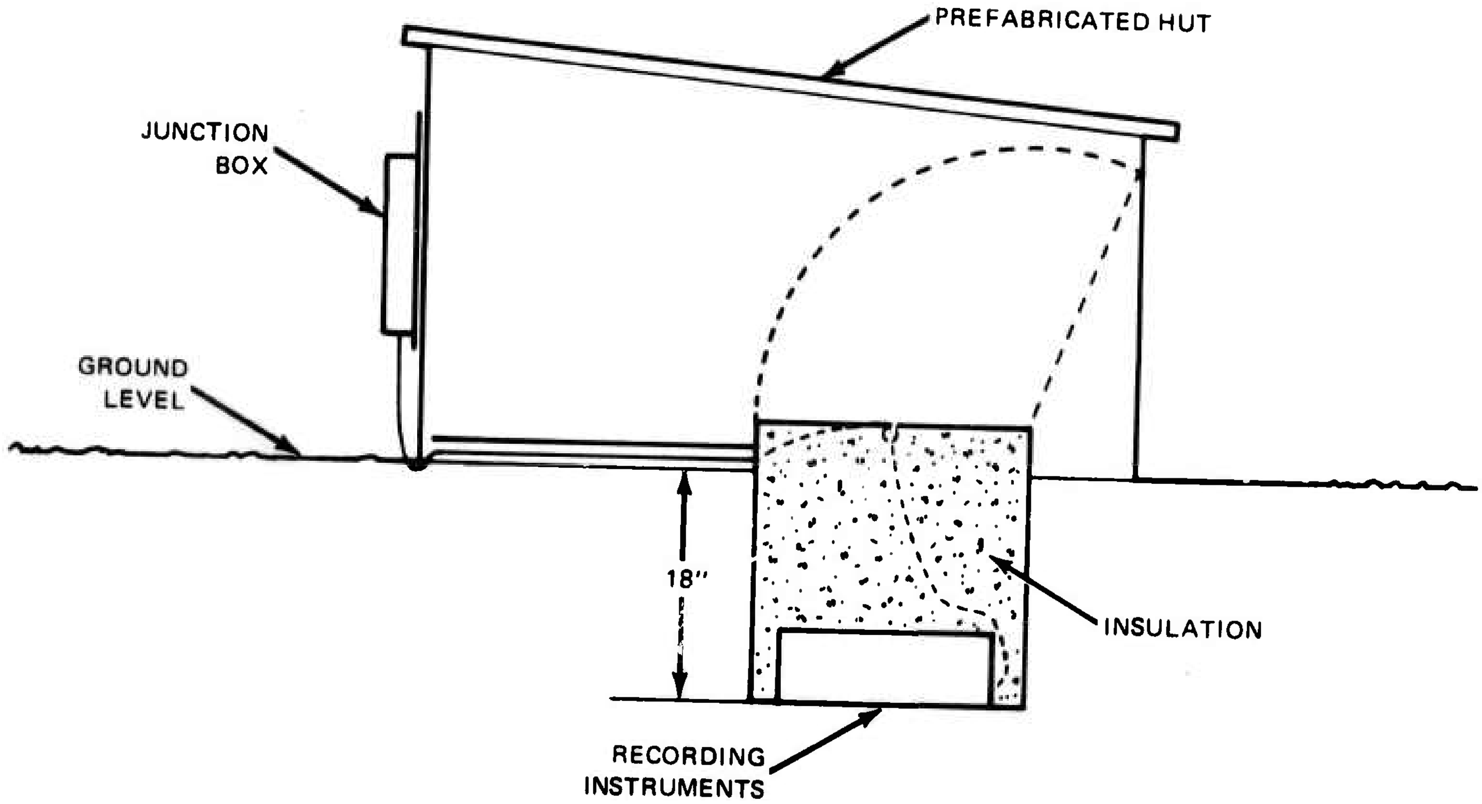

Figure 31. Side view of the recording facility

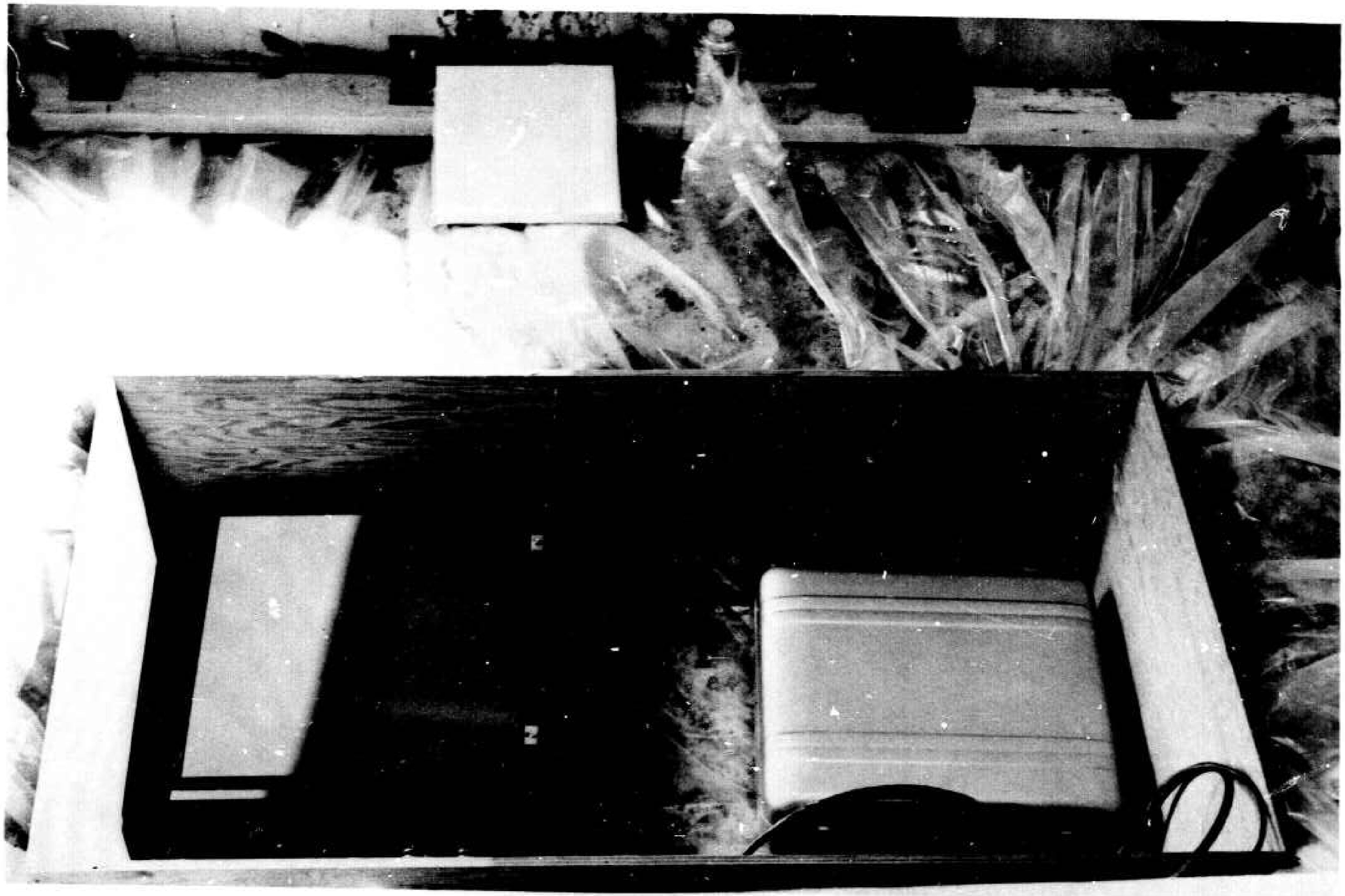

Figure 32. Photograph of plywood instrument enclosure inside recording hut used for final system tests in Garland, Texas

G 5713

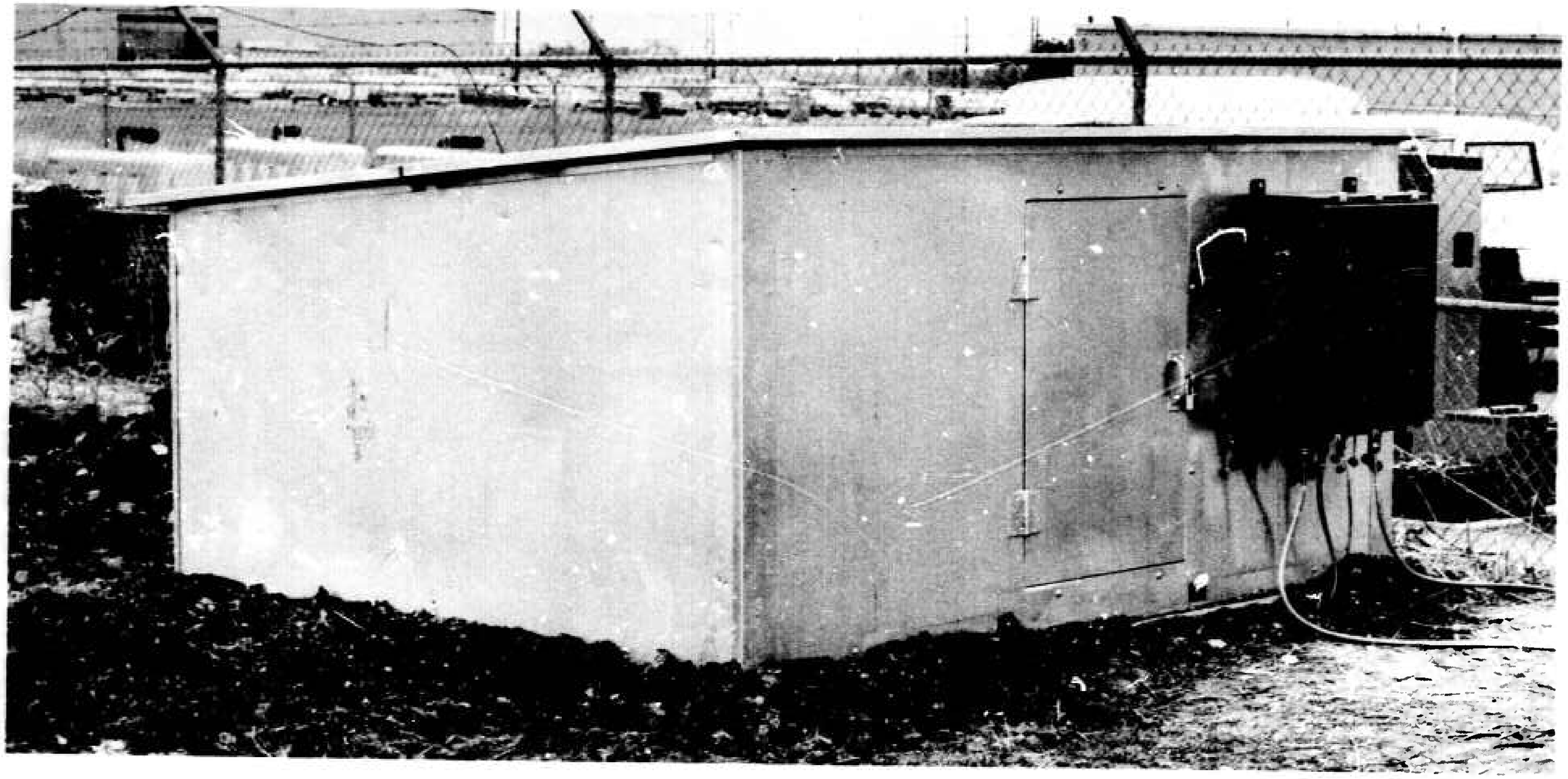

Figure 33. Photograph of prefabricated hut and junction box at the test facility in Garland, Texas

G 5714

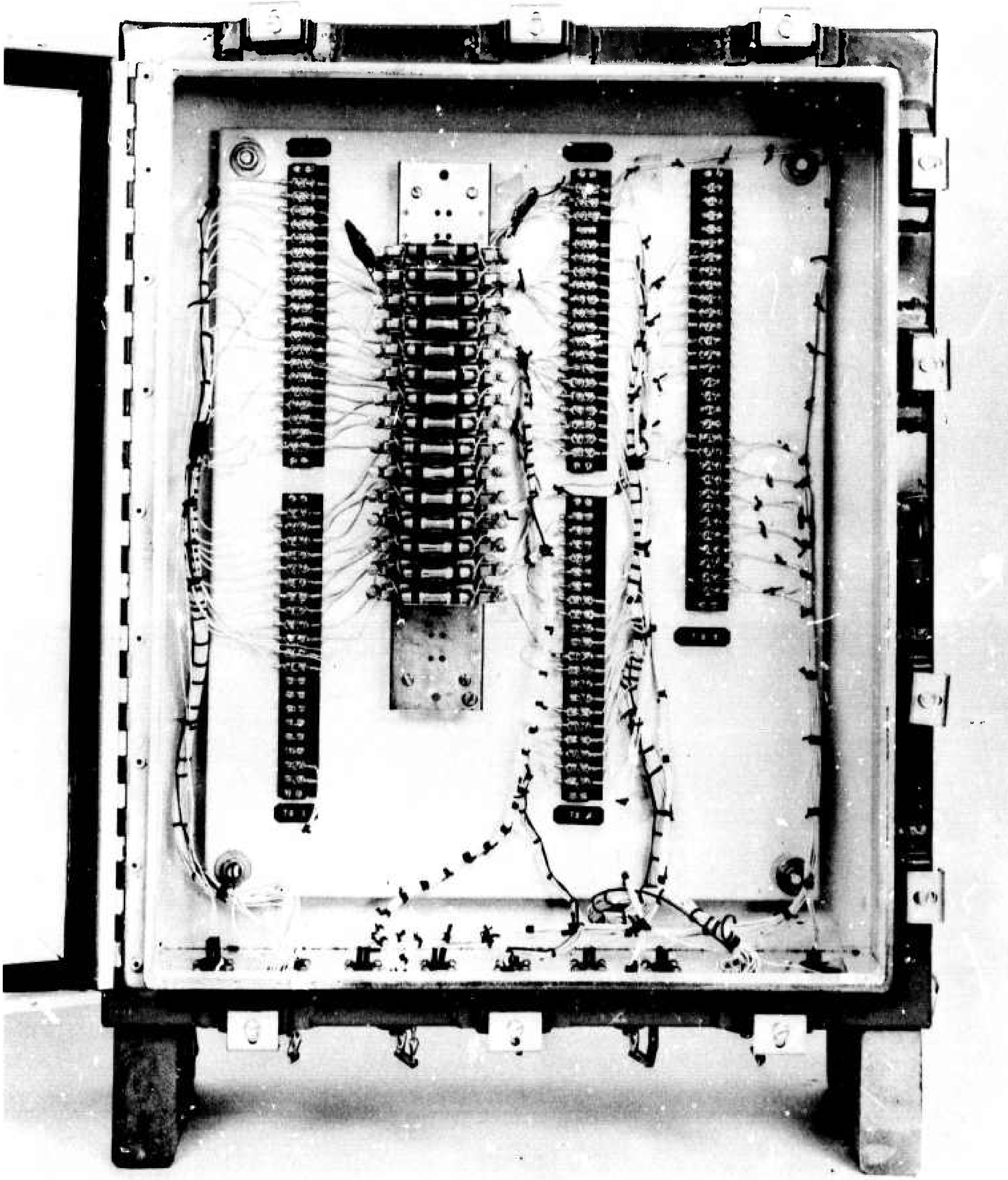

Figure 34. Photograph of junction box which is mounted on the outside wall of the recording facility

G 5715

d. A Tektronix Model 503 oscilloscope;

e. A Cornell-Dubilier Model 12ESW25 dc to ac inverter;

f. A WaveTek Model 110B function generator;

g. An Esterline-Angus Model T171B strip-chart recorder.

A circuit diagram of the service system is shown in figure 35. Equipment exterior to the control unit is enclosed by dashed lines. The control panel is mounted in an aluminum suitcase as shown in figure 36. The control panel provides the following operations:

a. Monitoring of strain signals preceding the signal control center;

b. Remotely actuating a stepper motor on the magnetic-tape unit in the recording facility and monitoring any of seven channels on the tape recorder;

c. Controlling the polarity, amplitude and duration of manual pulses to the EM calibrator;

d. Monitoring the EM calibrator current supplied by the function generator;

e. Remotely actuating a stepping relay in the lightning protection box at the strainmeter vault to select motors that position the capacitor plates on the strain transducer;

f. The lighting of neon tubes to indicate the motor selected and forward or reverse motor operation;

g. Allows either slow manual stepping of stepper motors on the coarse-adjust and fine-adjust mechanisms, or rapid stepping with a function generator signal operating through a logic circuit (figure 37);

h. Accumulates stepper-motor pulses on a single electro-mechanical counter.

Six counters in the lightning protector box (figure 38) at the strainmeter vault accumulate positive and negative counts for each of three stepper motors in the strain transducer. The difference between positive and negative counts on any motor can easily be converted to millimicrons of capacitor-plate displacement by multiplying the difference count by 4.93 (nominal).

11. SYSTEM POWER

The portable strain system is powered by thermoelectric generators burning propane fuel. These generators in use in other LRSM systems have proven to

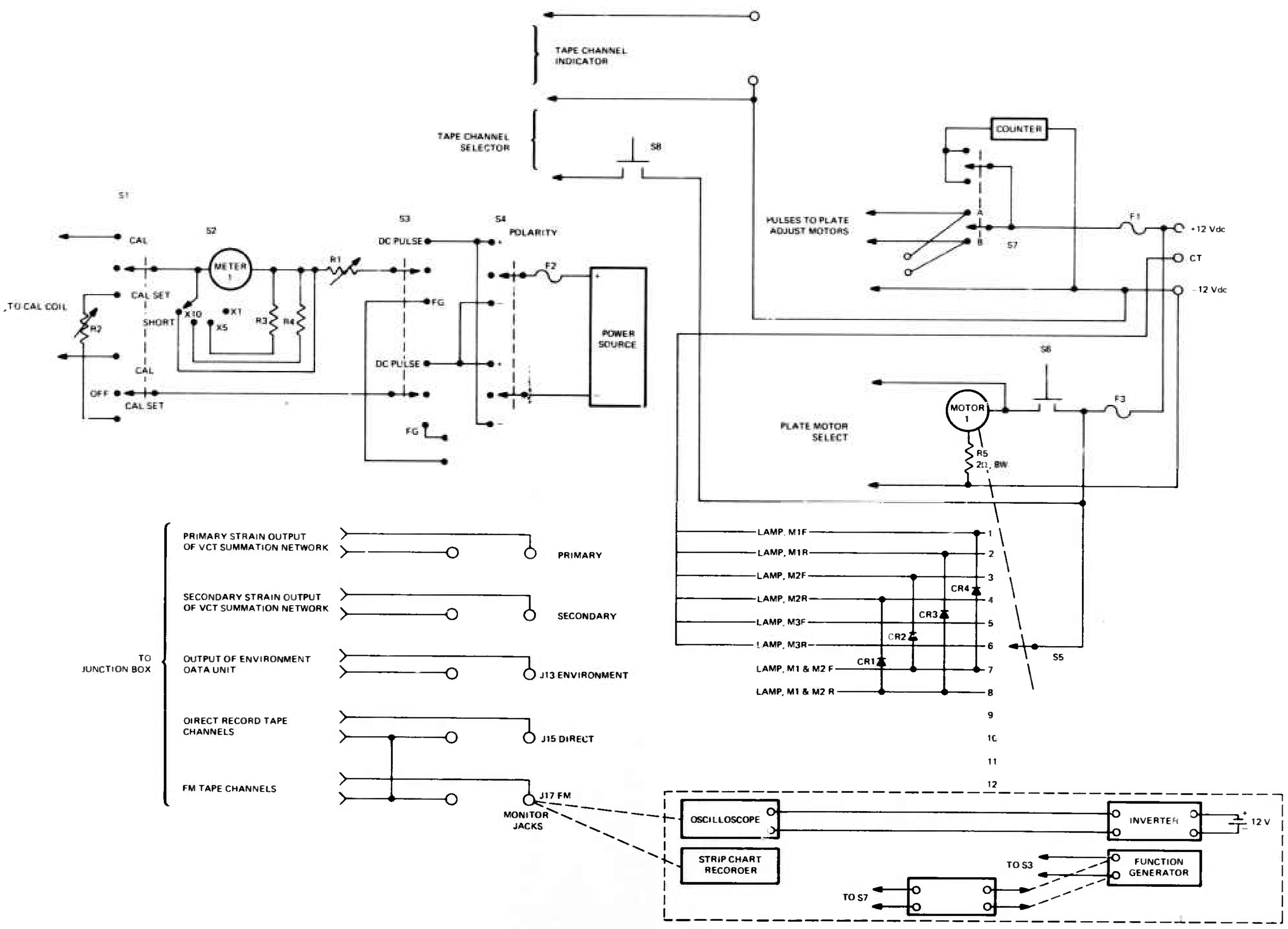

Figure 35. Circuit schematic of motor control and calibration system in service vehicle

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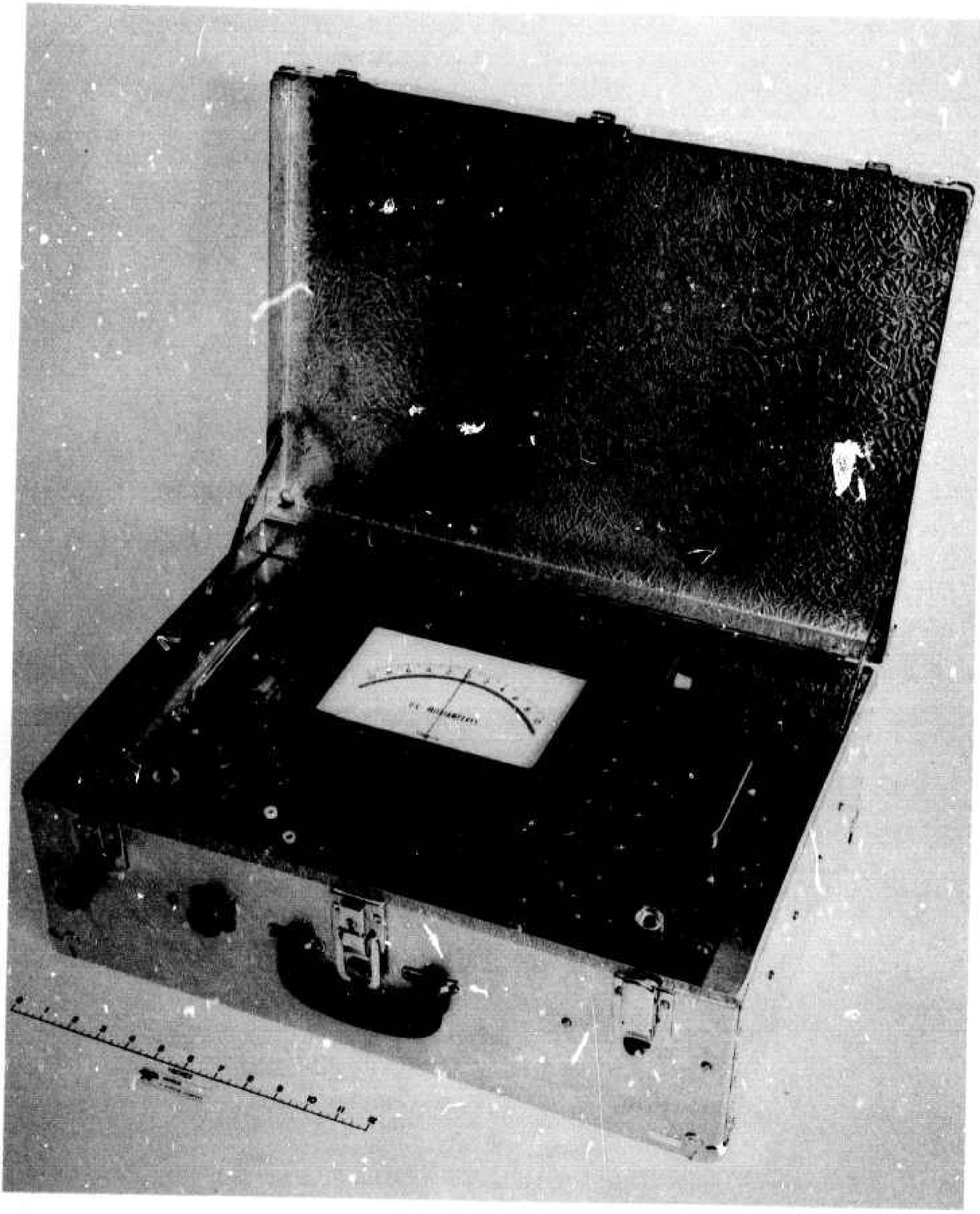

Figure 36. Photograph of control panel

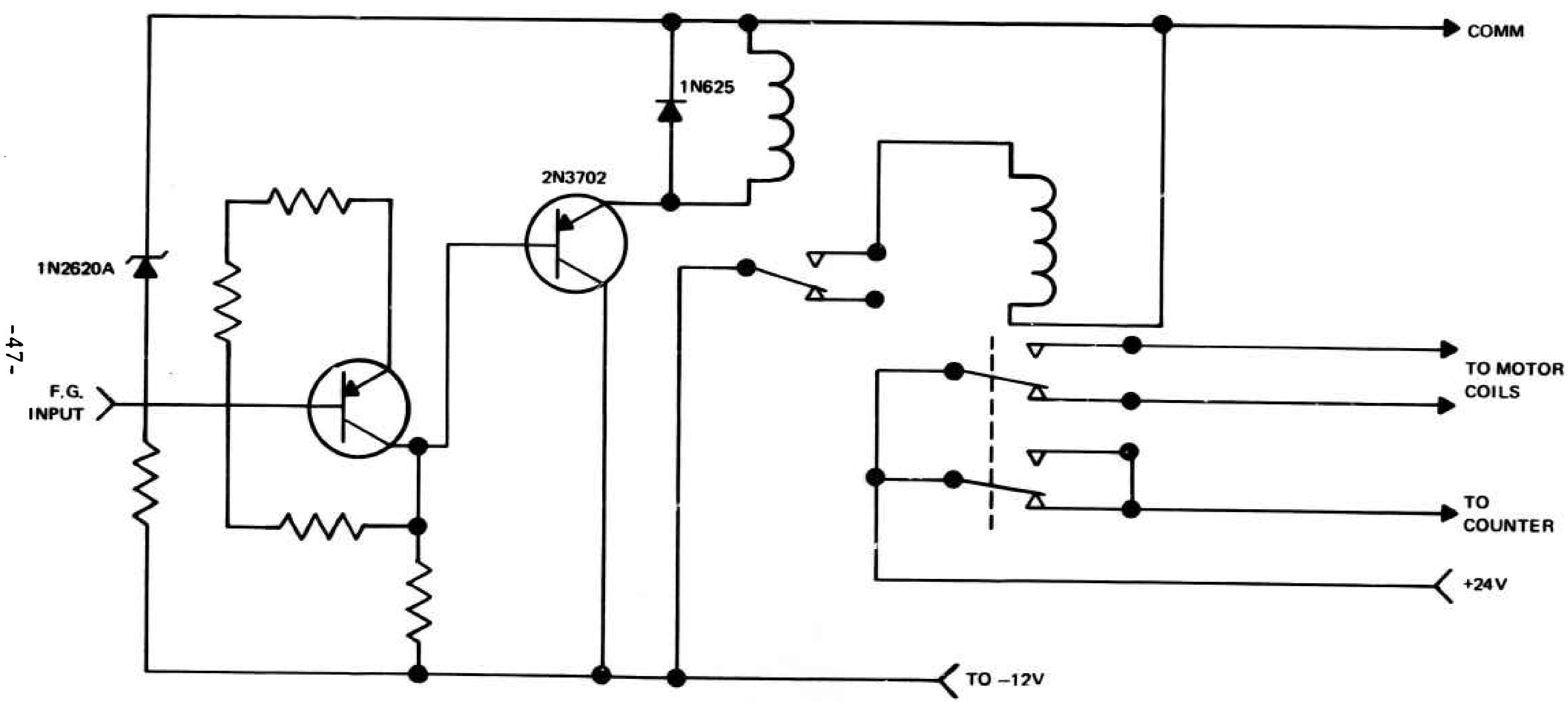

Figure 37. Logic circuit for controlling stepping rate of fine and coarse adjust motors by use of a function generator as a signal source

G 5718

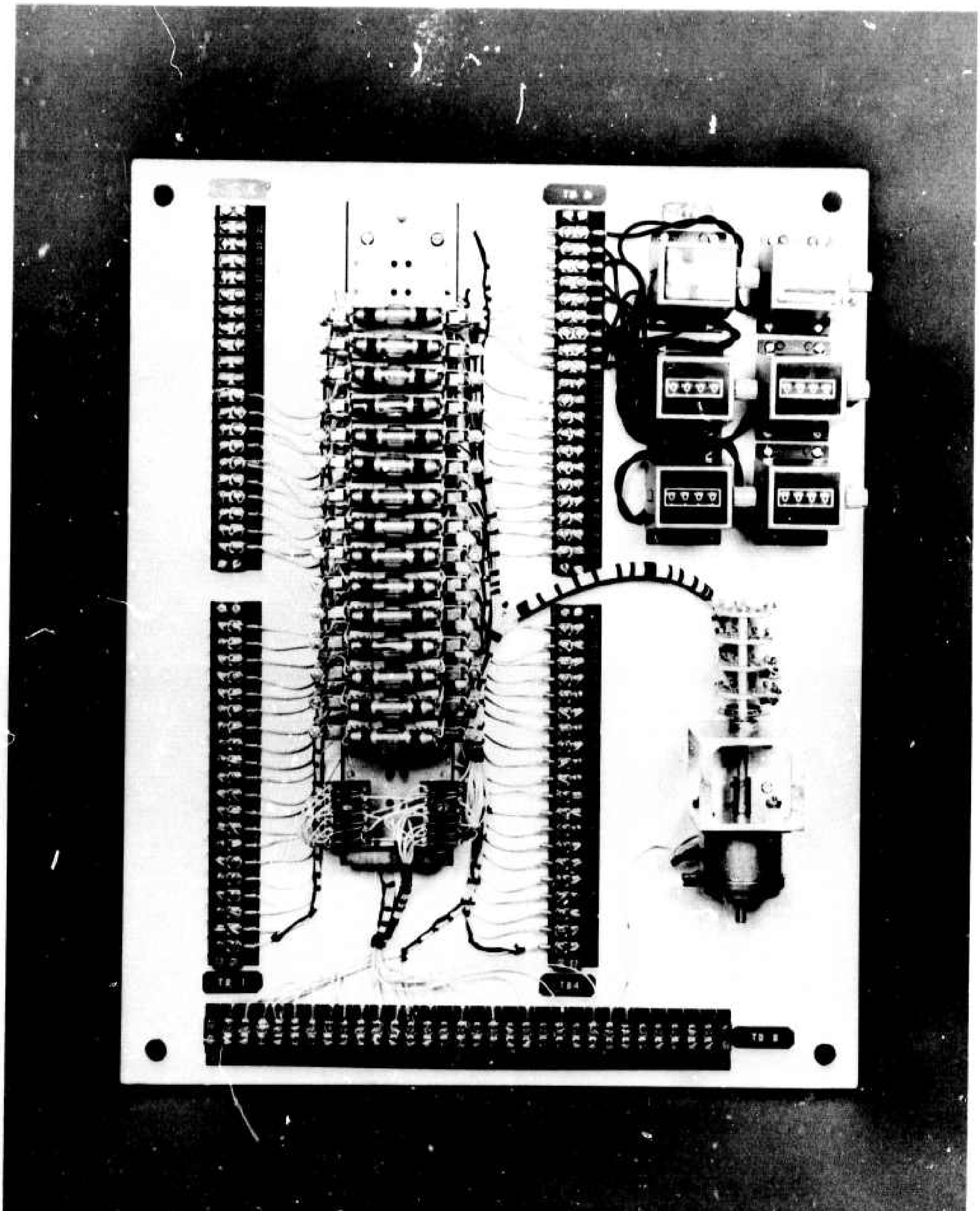

Figure 38. Panel from lightning protector box showing counters which accumulate positive and negative counts of the three stepper motors in the strain transducer

G 5719

be highly reliable and require low maintenance. The generator, 3M Company Model 520 with converter-limiter, is adjustable from 24 to 28 volts and delivers 42 watts of power. The strain system draws 34 watts. The generator operates across two 12-volt lead-acid storage batteries which provide the +12 Vdc, common, and -12 Vdc necessary for system operation. A resistive load in one side of the line can be used to balance the load. As an example, a 10-milliamp offset has been zeroed out with a resistive load with only a 3-watt loss of power. Propane fuel, readily available in 100-lb tanks, provides 14 days of operation per tank.

Operating from the power system are two 9-volt regulators which supply the strain transducers; a 9-volt regulator for the bridges in the temperature monitoring circuits; and a dc to dc converter that supplies +15, -15, and +5 volts to the digital-to-analog converter.

12. SYSTEM TESTS

Initial plans to provide a low cost system with a short delivery time depended heavily upon the use of a Sprengnether variable-capacitance transducer, Model VCT-200. An evaluation of the VCT-200 showed that the transducer met specifications reported by the manufacturer. Furthermore, its mechanical drift was sufficiently low. However, it was rejected for use in the portable strain system for the following reasons: (1) It was difficult to set up; (2) stray capacitance was strongly dependent upon the position of the cables leading to the plates; (3) the response of the transducer was not sufficiently linear (the manufacturer's specifications were not misleading); (4) offsets in the output data exceeded the equivalent level of minimum resolvable strain required; (5) the plate centering mechanism was erratic; (6) the transducer required 1-1/2 to 2 days to stabilize after the plate centering mechanism was activated; (7) the linear range of the transducer was less than 8 microns at the required transducer sensitivity.

To satisfy system specifications, an existing experimental single-plate I/C (inverse capacitance) Detector, Geotech Model 33377, was mounted on a Blayney lineal motion reducer. In a series of oven tests and operating tests in the 16.4-meter deep test vault at Garland, Texas, a dual capacitor with a moving center plate and two fixed end plates was developed. The detector has a sensitivity of 40 millivolts per micron at a plate spacing of 200 microns. By converting from a single pair to two pairs of plates, the output linearity is increased from 0.99 percent at 10 microns to 0.12 percent at 10 microns, based on a stray capacitance of 25 picofarads. An additional detector with the lineal motion reducer reversed in direction was added to the design to compensate for temperature effects on the lineal motion reducer, and to provide a backup transducer. Figure 39 shows a test record of the strain transducer output and temperature output in the 16.4-meter test shaft in Garland under conditions of both small and large temperature changes. The electronic noise level, which is marginal in this test, was reduced to the required limit of 70 microvolts at the transducer output by selecting Amelco 709 integrated circuits of low noise level. Approximately 25 percent of the 709 chips are satisfactory. A

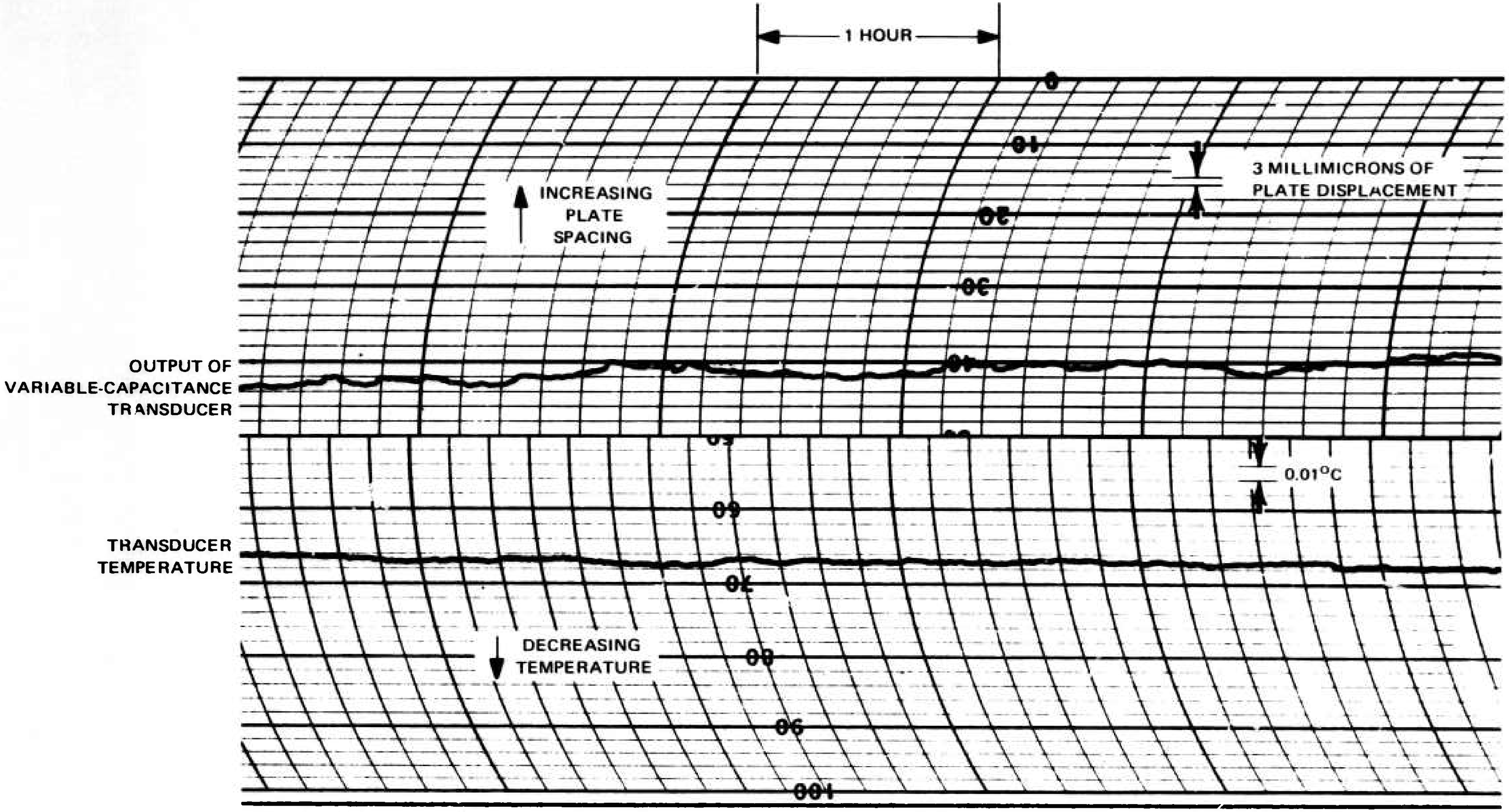

Figure 39. Test record of the strain transducer output and temperature output reflecting a change in plate displacement of 15 millimicrons for a temperature change of 0.01 degree centigrade in the 16.4-meter deep test shaft in Garland. A dual capacitor on a single lineal motion reducer was used.

noise level of 70 microvolts is equivalent to a plate displacement of approximately 1.5×10^{-9} meters or a strain equivalent of 2.5×10^{-10}. The ratio of minimum detectable strain (5×10^{-10}) to the strain equivalent of transducer noise is therefore 2:1.

Tests on the complete system were conducted in an open field at the Geotech facility in Garland, Texas. All operating conditions anticipated in the field relating to power; thermal isolation; and service vehicle operation were maintained during system tests except for the substitution of a 0.85-meter length of quartz tube in place of the 6-meter tube, as shown in figure 40. The 2.6-meter deep vault in figure 40 was constructed at the Geotech facility to simulate temperature conditions in a 2.6-meter trench installation.

The response of the strainmeter to quasi-static strain is given in figure 41. The response curve is obtained using a filter with a high-frequency cutoff of 0.1 Hz. The response is flat from dc to 0.1 Hz; is down 2 dB at 0.1 Hz; and has a cutoff rate of -10 dB per octave beyond 0.1 Hz. The 0.1 Hz filter will probably be replaced in the field by a 0.01 Hz filter.

The response of the voltage control circuit to high count rates was checked on an oscilloscope and found to meet the design requirements of 50 offsets per second.

The response of the total strain circuit was checked by operating both the EM calibrator and the VCT plate positioning motors at a high stepping rate, recording the signal on magnetic tape and recording the playback signal on a high-frequency oscillograph. The response of the system to a precisely known signal free of environmentally induced strain background noise was obtained by injecting sinusoidal signals at various frequencies and voltage levels into the signal control center. The output of the voltage control circuit in response to a 5-volt peak-to-peak sinusoidal signal at 0.1 Hz, producing a maximum of 8 offsets per second, is shown in figure 42. An offset repetition rate of 12 per second is the maximum repetition rate predicted for the system with a frequency response that is flat to 0.1 Hz in response to the quasi-static strain signal from a magnitude (M) 6.5 event at 30 km. The DAC can accommodate a repetition of 50 per second, but the recorder is flat to only 5 Hz at 0.03 ips. Furthermore, high-frequency traveling waves in the region of 1 Hz are expected to produce offset-repetition rates of the order of 30 per second with a 0.1 Hz filter. By using a 0.01 Hz cutoff with a 12 dB per octave falloff, the rate will be reduced to less than one offset per second for the high-frequency traveling waves.

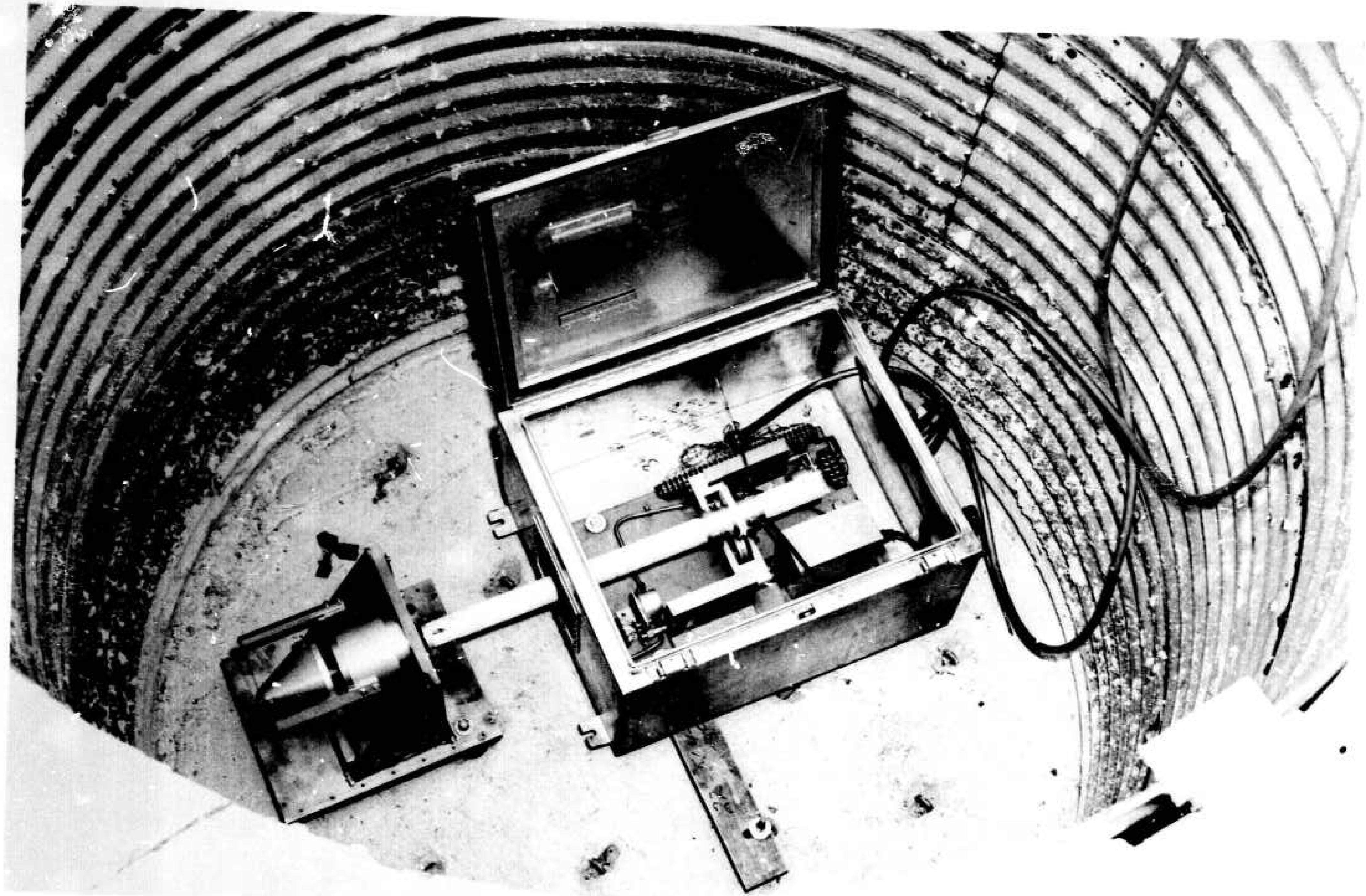

Figure 40. Short strainmeter in 2.6-meter deep test vault in Garland, Texas

G 5721

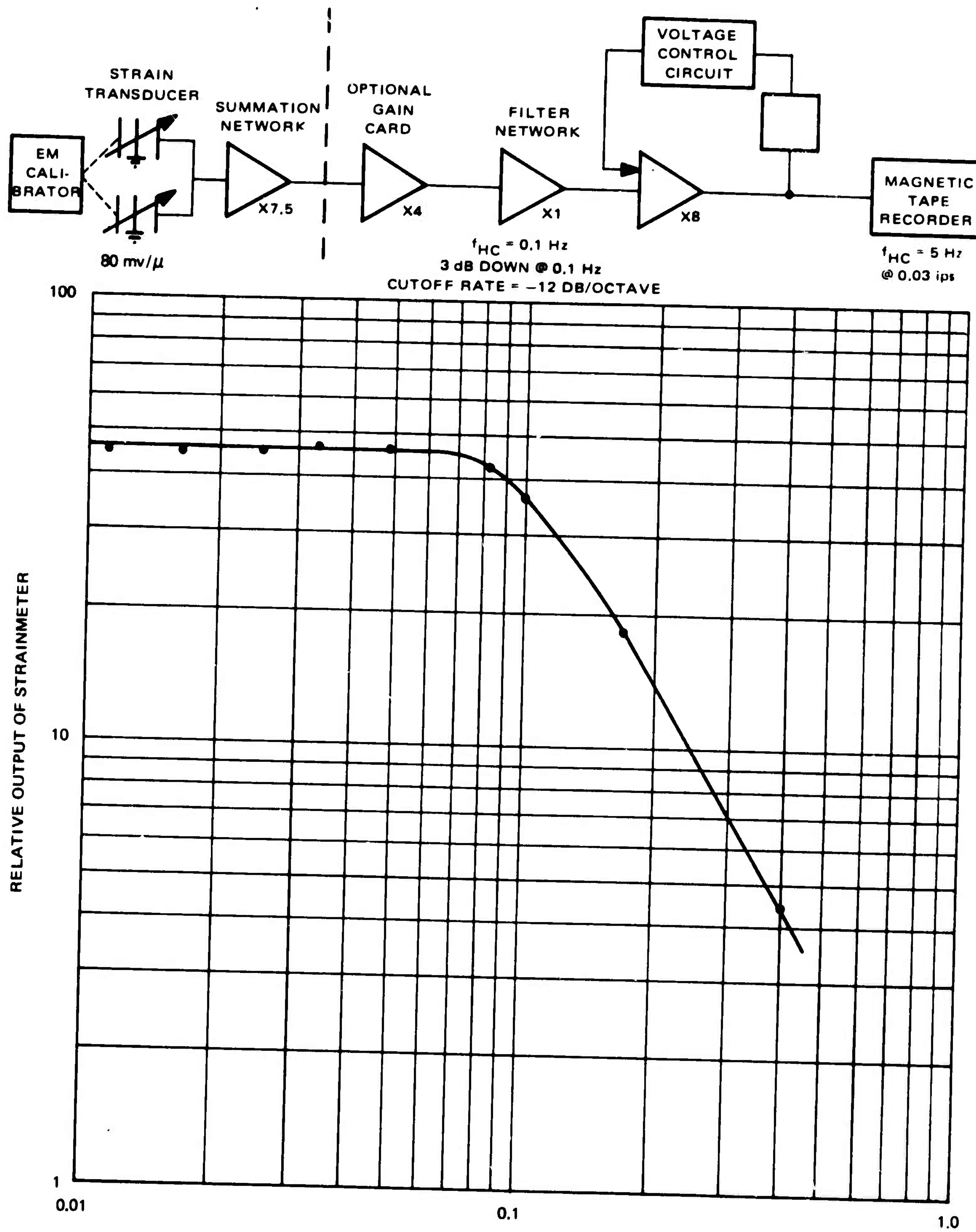

Figure 41. Amplitude response of the portable strainmeter to constan` differential pier displacement

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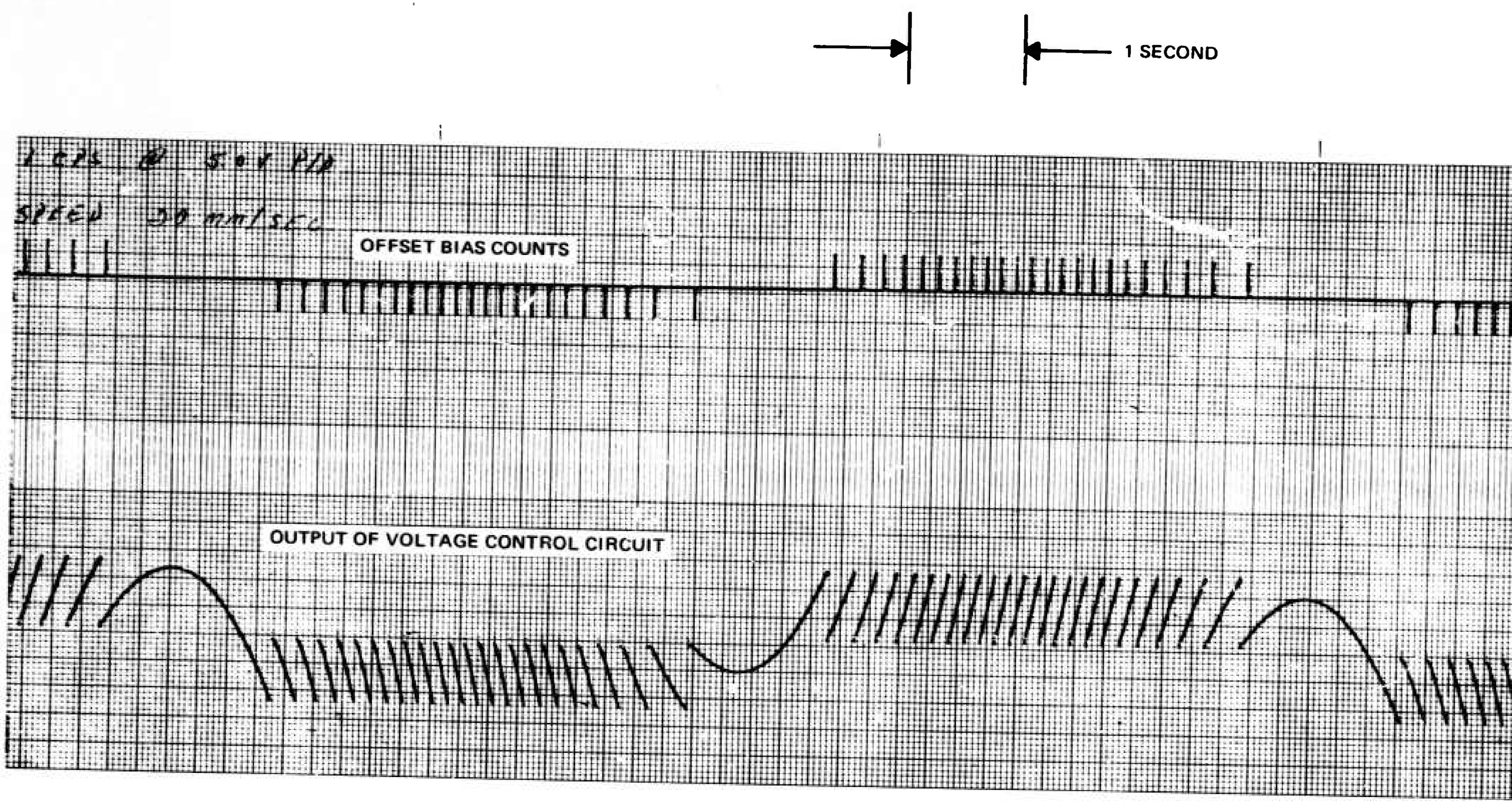

Figure 42. Output of voltage control circuit in response to a 5-volt peak-to-peak sinusoidal signal at 0.1 Hz injected at the input to the signal control center, producing offsets at a maximum rate of 8 per second

G 5723

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APPENDIX 1 to TECHNICAL REPORT NO. 70-6

STATEMENT OF WORK TO BE DONE
(AFTAC PROJECT AUTHORIZATION NO. VELA T/8703/S/ASD)
as amended by P002

JUL 7 1969

50046

Statement of Work to be Done
AFTAC Project Authorization No. VELA T/8703/ASD
Amendments # 6 and # 7

The following subpargraphs are added to Task C, Special Projects.

(1) Design, Fabricate, and assemble six portable strainmeters and associated Recording Equipment for measurements of strains of 5 X 10-10 or better over a 6-meter interval in the period range from 10 seconds to DC. A simple, reliable recording system capable of at least 1 week's unattended operation is required. Two sets of installation and test equipment will be required to assure satisfactory set-up of the group of instruments. The details of the system design and proposed field installation techniques should be submitted and approved in writing by the Government prior to fabrication and assembly of the systems.

(2) The strainmeter systems will tentatively be evaluated in the field concurrently with deployment around a large event to record induced strains. Details of the event to be monitored and desired recording arrangement will be provided by the Government.

(3) Technical data to be provided by the Government and approval of technical aspects of recommended equipment configurations and other features of the required measurement programs will be provided by the Contracting Officer.

APPENDIX 2 to TECHNICAL REPORT NO. 70-6

SYSTEM CHARACTERISTICS - PORTABLE STRAINMETER SYSTEM

SYSTEM CHARACTERISTICS - PORTABLE STRAINMETER SYSTEM

PURPOSE

The portable strainmeter system is designed to detect and record strains of 5×10^{-10} or smaller over an interval of 6 meters in the period range from 10 seconds to dc. Differential ground displacement is measured with a variable-capacitance transducer (VCT).

The strainmeter is anchored to bedrock in a trench 2 to 3 meters deep and buried to reduce temperature effects. Signal control modules, a magnetic tape recorder, and a time code receiver are located in a recording facility at a distance of at least 65 meters from the strainmeter.

Temperature characteristics of the system are measured in the laboratory and field and the temperature is monitored in operation to permit correction of the strainmeter output for temperature-induced drift.

Unattended operation for periods of at least one week is required.

A thermoelectric generator furnishes power. A service vehicle containing calibration and monitoring equipment is plugged into a junction box at the recording facility. When operation is terminated at a trench site, all instrumentation and materials are removed with the exception of 6 meters of quartz tubing, 6 meters of steel culvert, and two wooden access shafts. The major components of the system are as follows: one (1) strainmeter vault; two (2) vault accessways; one (1) strainmeter, one (1) strain transducer; one (1) recording facility; two (2) offset-biasing circuits; one (1) signal control center; one (1) junction box; one (1) calibration control; one (1) power source; one (1) power system; one (1) temperature monitoring system; one (1) pressure monitoring system; one (1) electromagnetic calibrator; one (1) anchor; one (1) service vehicle; one (1) vault protector; one (1) Magnetic Tape Recorder, Model 17373; one (1) Time Code Receiver, Specific Products Model T-60A; one (1) Strip Chart Recorder, Esterline-Angus Model T171B; one (1) Dc to Ac Inverter, Cornell-Dubilier Model 12ESW25; one (1) Oscilloscope, Tektronix Model 503.

OPERATING CHARACTERISTICS	DESIGN GOALS
Sensitivity	Will resolve strains of 5×10^{-10} or better from dc to 0.1 Hz
Maximum strain ranges	5×10^{-7} and 5×10^{-6}
Frequency response	Low pass maximally flat, 0.1 Hz knee, 12 dB roll-off
Linearity	±3% of best straight line over the full deviation range of the tape recorder

Operating tolerance	
Strainmeter vault	0.003°C diurnal change, 3°C/month (seasonal rate of change)
Recording facility	6°C (diurnal change), 12°C/month (seasonal rate of change)

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Security Classification

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11. SUPPLEMENTARY NOTES 5 times 10 to the minus 10 power	12. SPONSORING MILITARY ACTIVITY Hq USAF (AFTAC/VELA Seismological Center) Washington, D. C. 20333

13. ABSTRACT

Six portable strainmeter systems were designed and built for deployment in mine tunnels and shallow trenches to measure strains induced by high yield underground events at epicentral distances as short as 30 km. The system is designed to detect earth strains of 5×10^{-10} or smaller over a horizontal interval of 6 meters in the period range 10 seconds to dc, and to record the signals on magnetic tape. Strains are detected by a variable-capacitance transducer attached to a quartz-tube translating member. Output signals are maintained within a dynamic range of 30 dB for an input-signal range of 66 dB by an offset biasing technique which uses a precision voltage-level detector and a digital-to-analog converter. Temperature measurements are resolvable to within 0.001 degree Centigrade by the same offset biasing technique. The strainmeter is calibrated with a temperature-compensated electromagnetic calibrator mounted at the fixed end of the quartz tubing. The strain detector is calibrated and the capacitor plates positioned over a range of 12×10^{-6} meters in steps of 5×10^{-9} meters by use of a stepping motor and motion reducer.

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Security Classification